Nuclei in the Cosmos School
2025

STELLAR EVOLUTION

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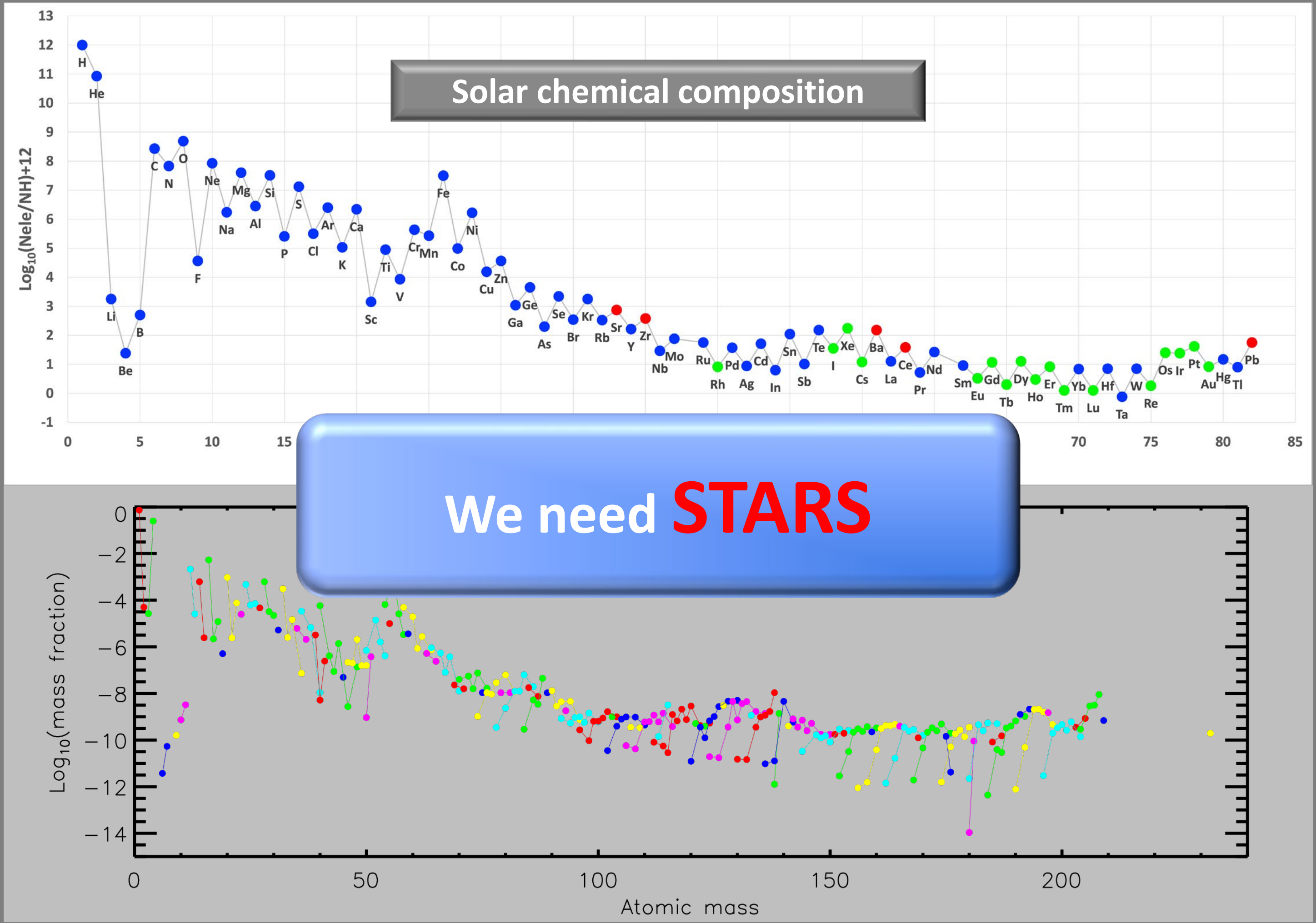
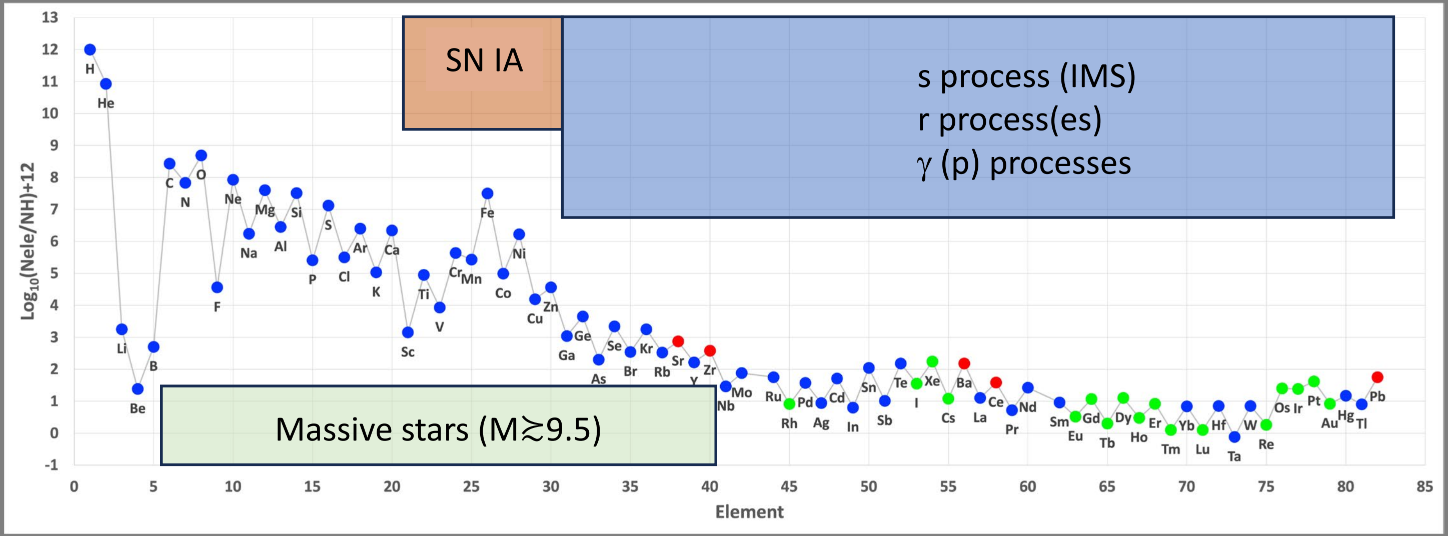


Solar chemical composition
Log10(Nele/NH)+12
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Xe
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
We need STARS
Log10(mass fraction)
Atomic mass

Solar chemical composition



Golden rules

The temperature in the inner core of a star increases only as a consequence of the gravitational contraction

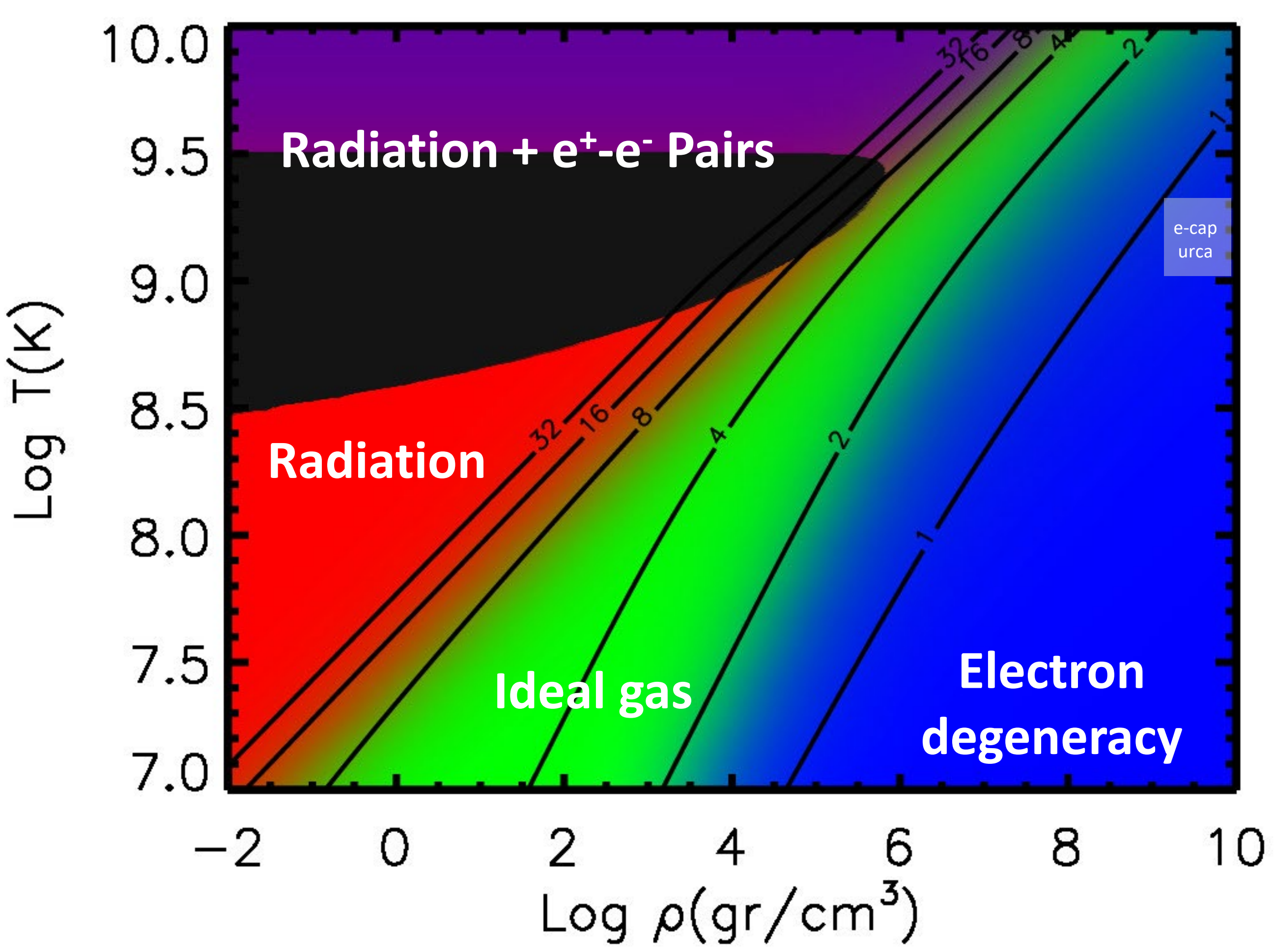
According to the Virial theorem, a fraction of the energy gained by the contraction leads to the increase of the temperature while the remaining part is lost outward (the Luminosity)

$$\mathbf{Log(T) \propto Log(\mu^3 M^2) + \frac{1}{3} Log(\rho)}$$

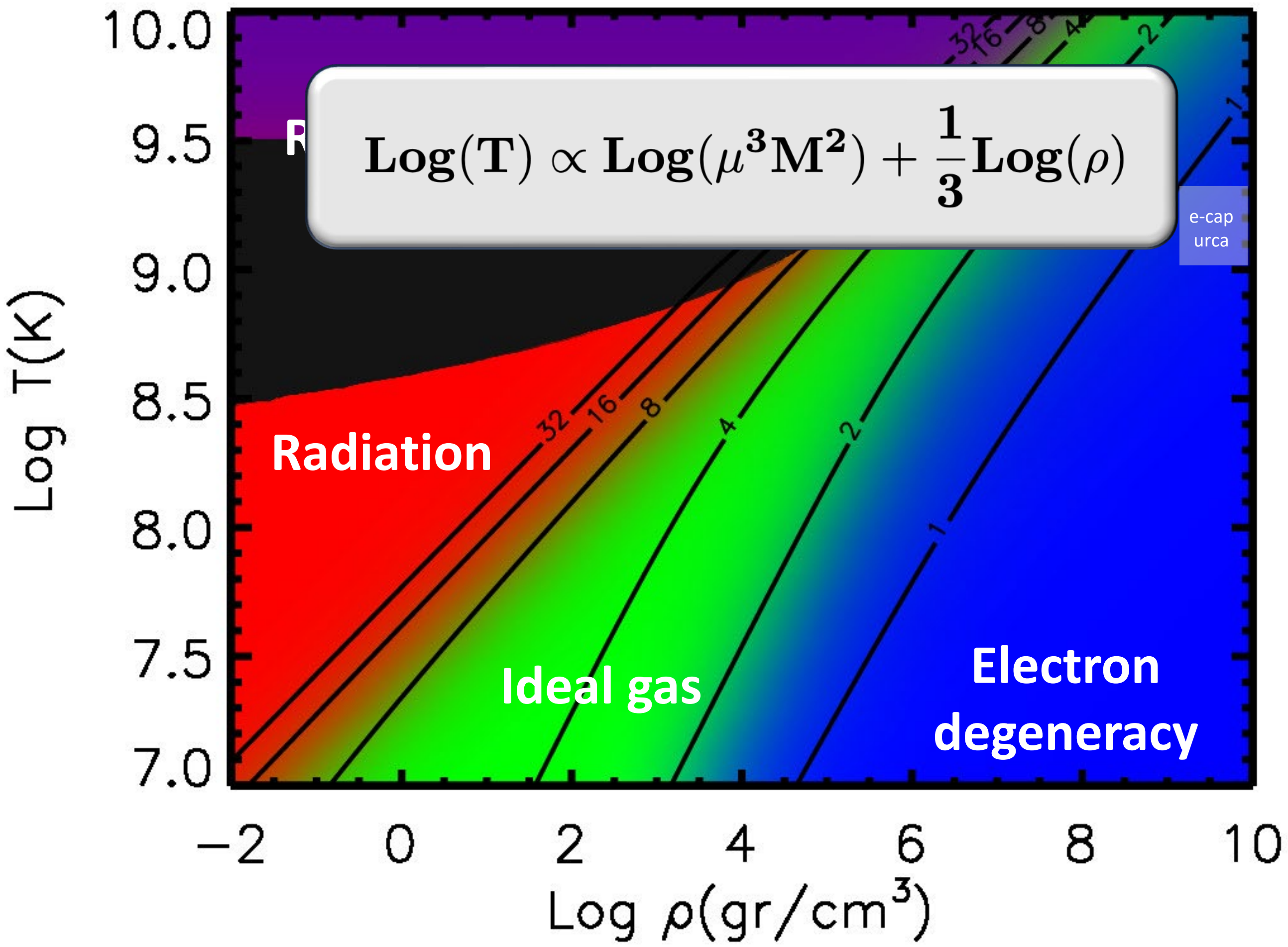
Hydrostatic equilibrium + EOS (Perfect Gas + radiation)

$$\mathbf{L \propto M^3}$$

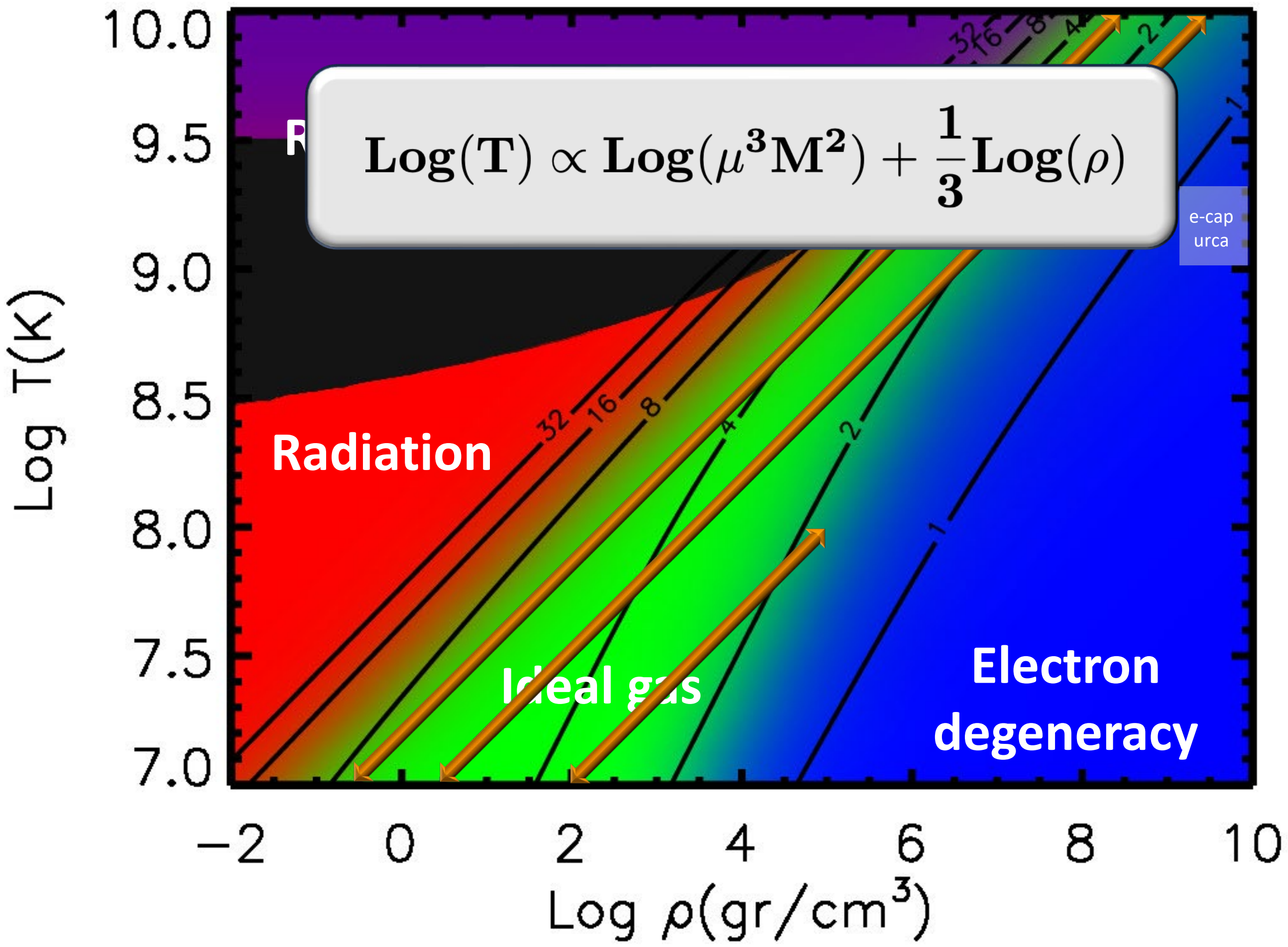
+ radiative equilibrium (valid in self regulating conditions)

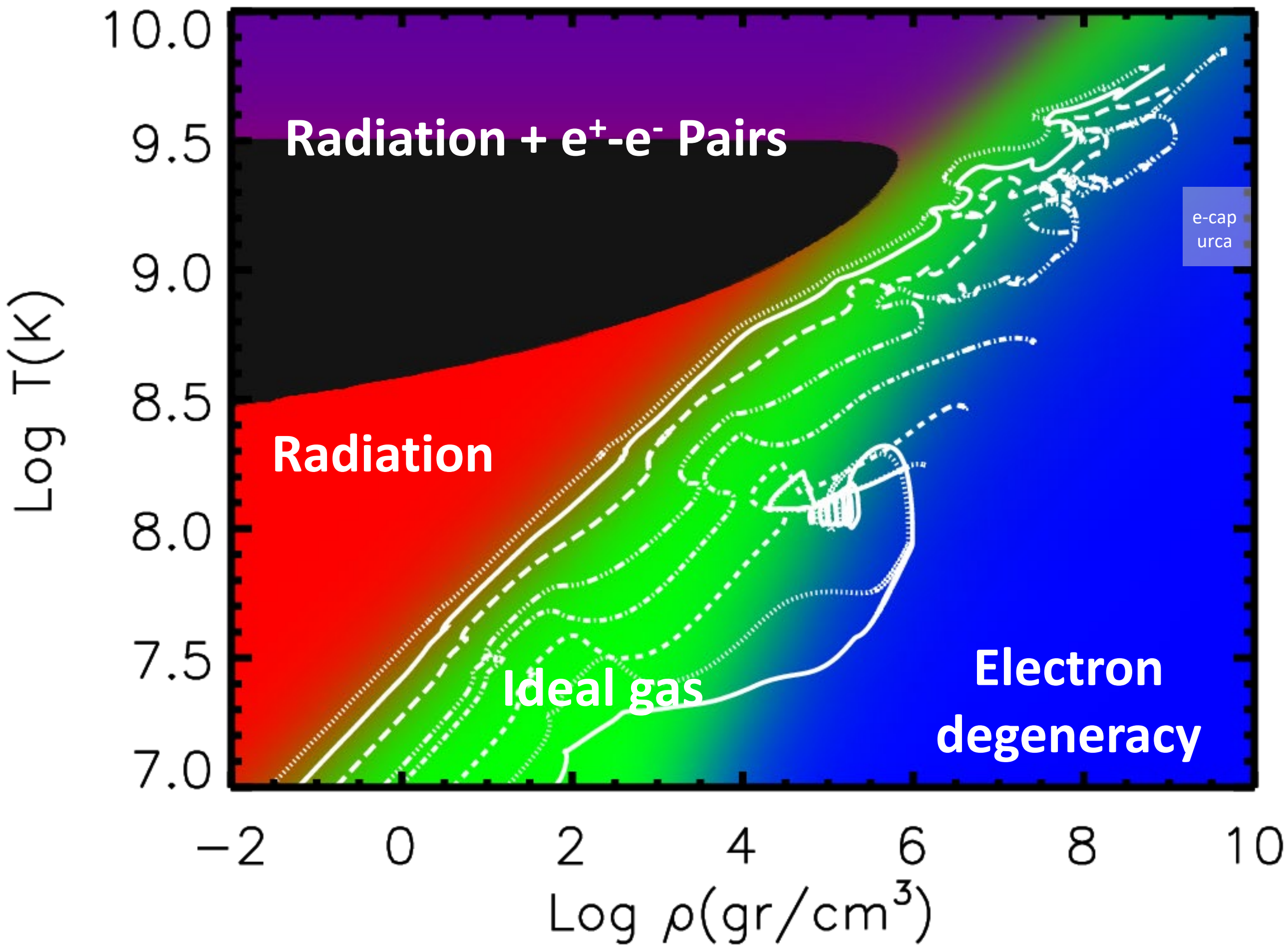

10.0
9.5
9.0
8.5
8.0
7.5
7.0
Log T(K)
−2
0
2
4
6
8
10
Log ρ(gr/cm³)
Radiation + e⁺-e⁻ Pairs
Radiation
Ideal gas
Electron
degeneracy
e-cap
urca
32
16
8
4
2
1

$$\mathrm{Log(T)} \propto \mathrm{Log}(\mu^3 M^2) + \frac{1}{3}\mathrm{Log}(\rho)$$

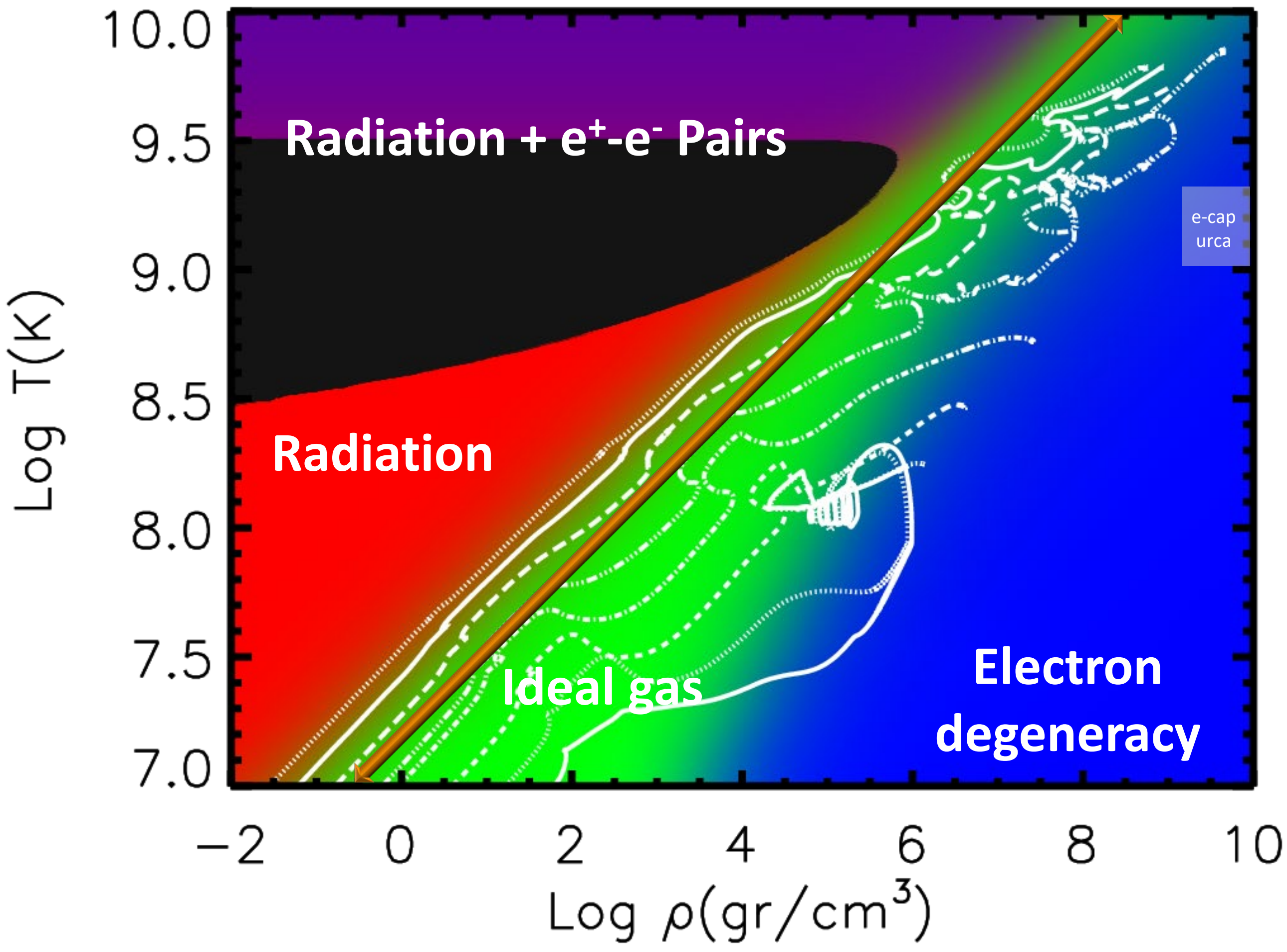


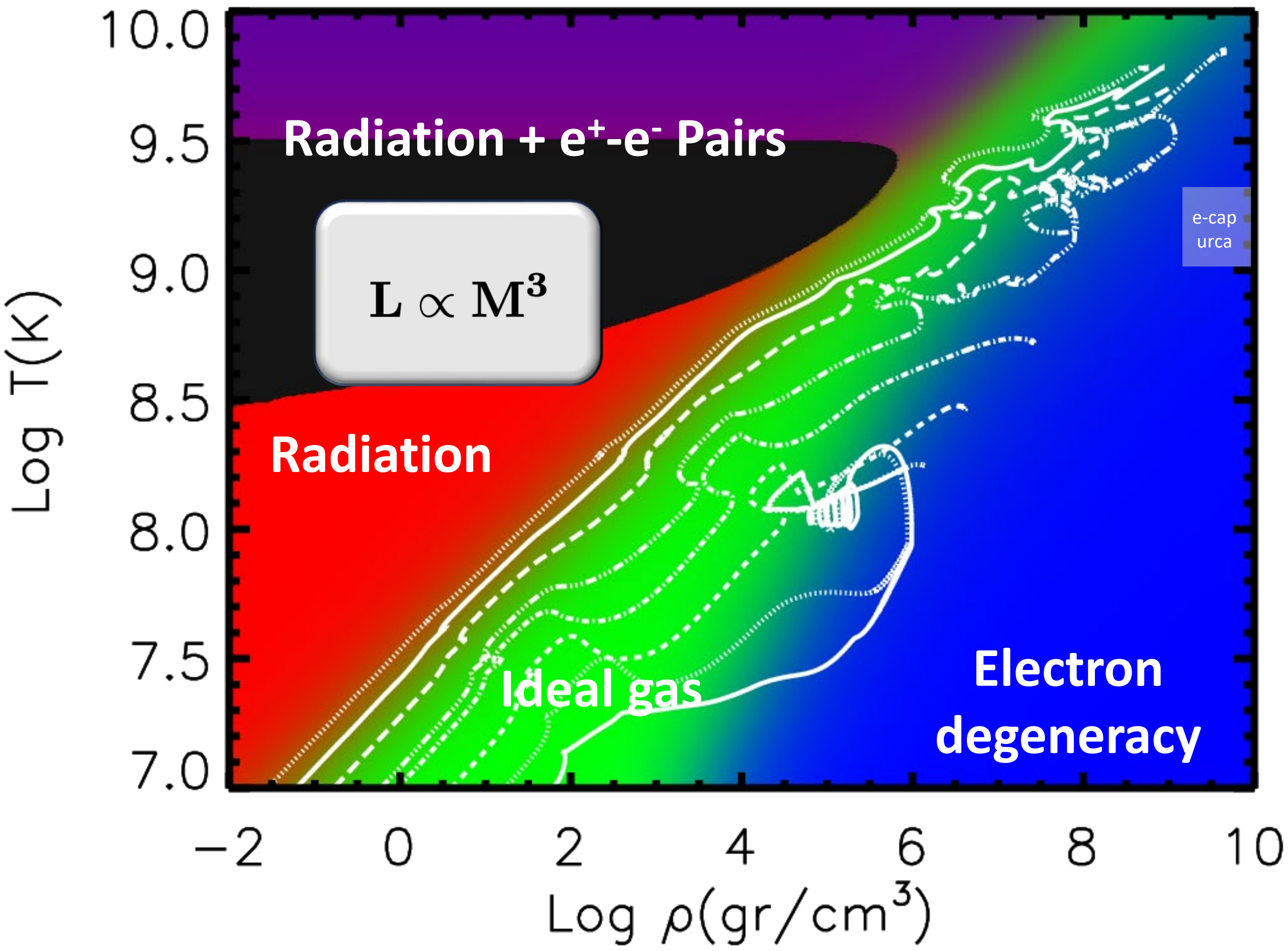
$$\mathrm{Log(T)} \propto \mathrm{Log}(\mu^3 \mathrm{M}^2) + \frac{1}{3}\mathrm{Log}(\rho)$$

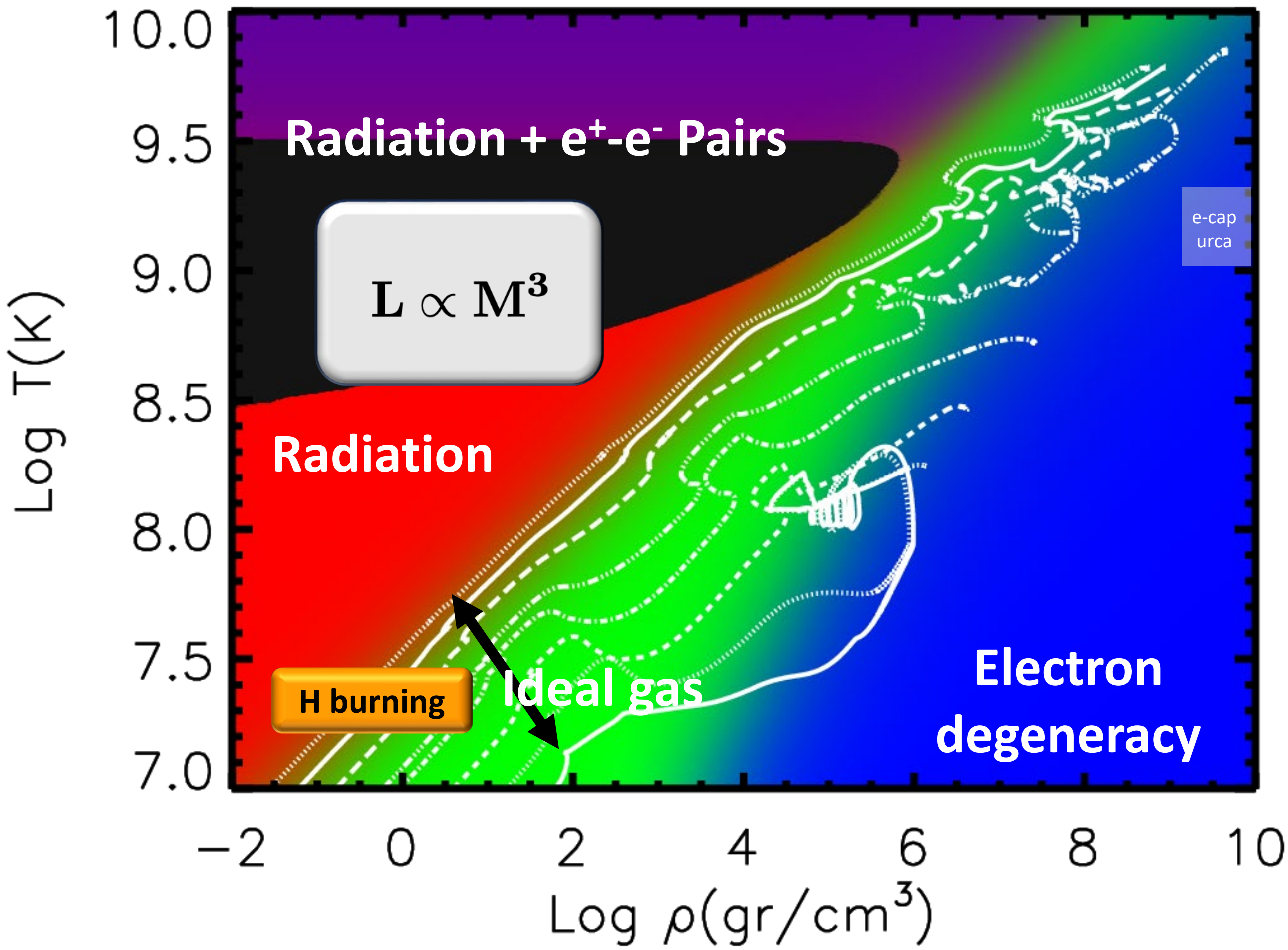




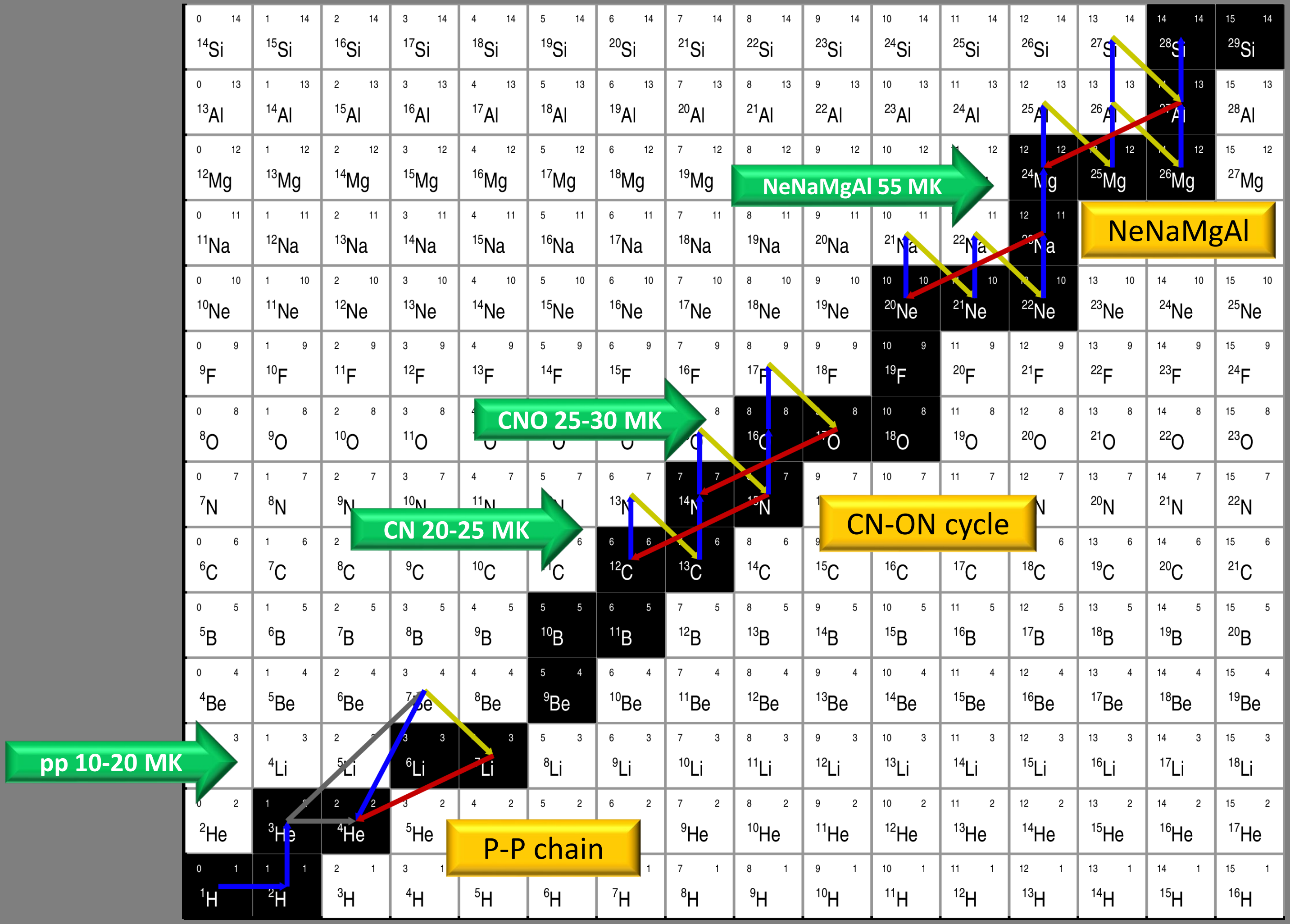
Radiation + e^+-e^- Pairs
Radiation
Ideal gas
Electron degeneracy
e-cap
urca
Log T(K)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10
Log ρ(gr/cm³)

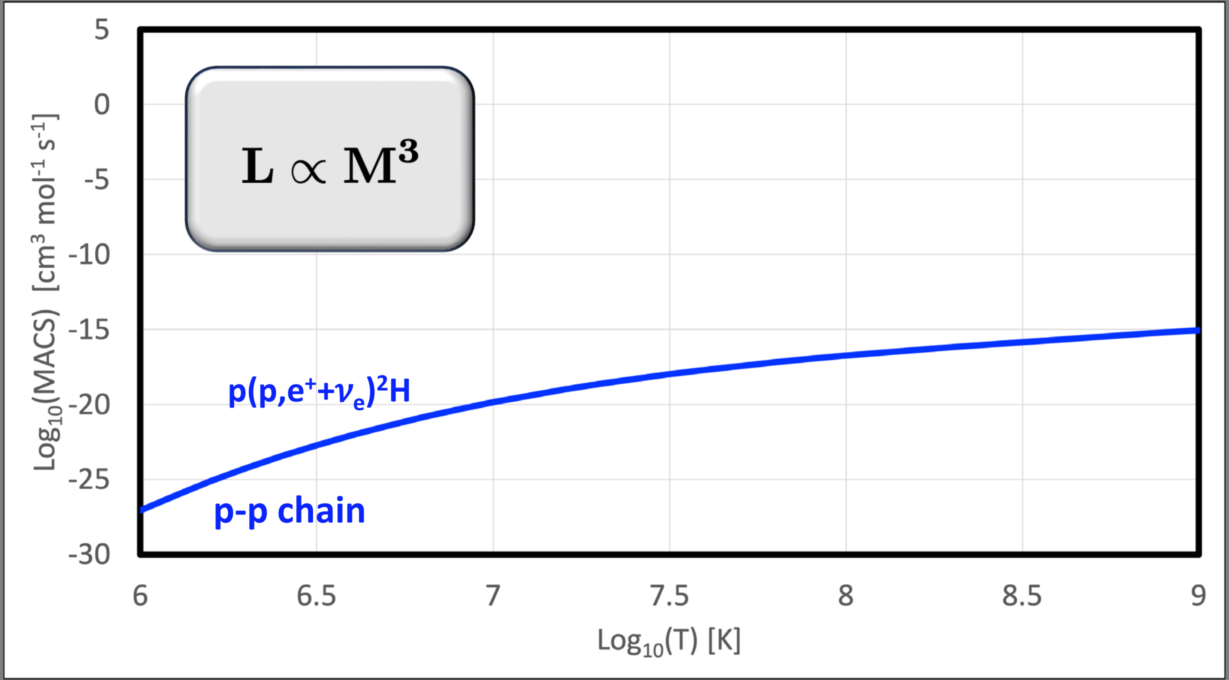

Radiation + e+-e- Pairs
Radiation
Ideal gas
Electron degeneracy
e-cap
urca
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Log T(K)
−2
0
2
4
6
8
10
Log ρ(gr/cm3)


Radiation + e+-e- Pairs
L ∝ M³
Radiation
Ideal gas
Electron
degeneracy
e-cap
urca
Log T(K)
Log ρ(gr/cm³)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10



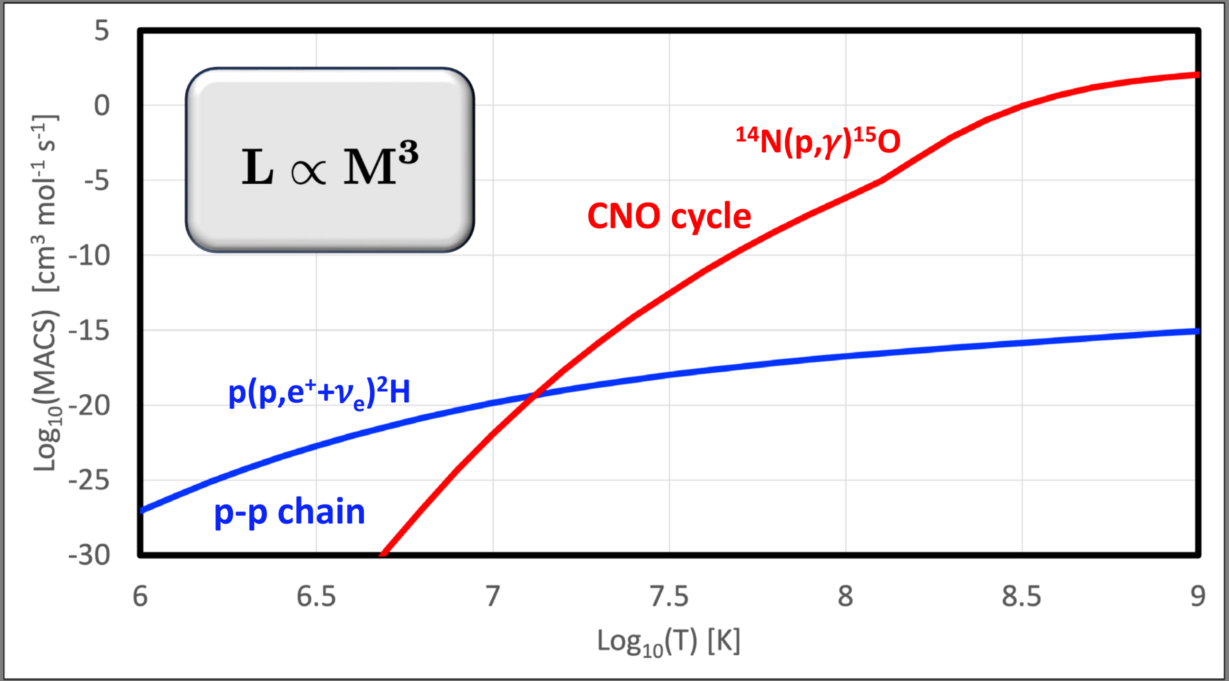
Radiation + e+-e- Pairs
L ∝ M3
Radiation
H burning
Ideal gas
Electron degeneracy
e-cap urca
Log T(K)
Log ρ(gr/cm3)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10


NeNaMgAl 55 MK
NeNaMgAl
CNO 25-30 MK
CN 20-25 MK
CN-ON cycle
pp 10-20 MK
P-P chain

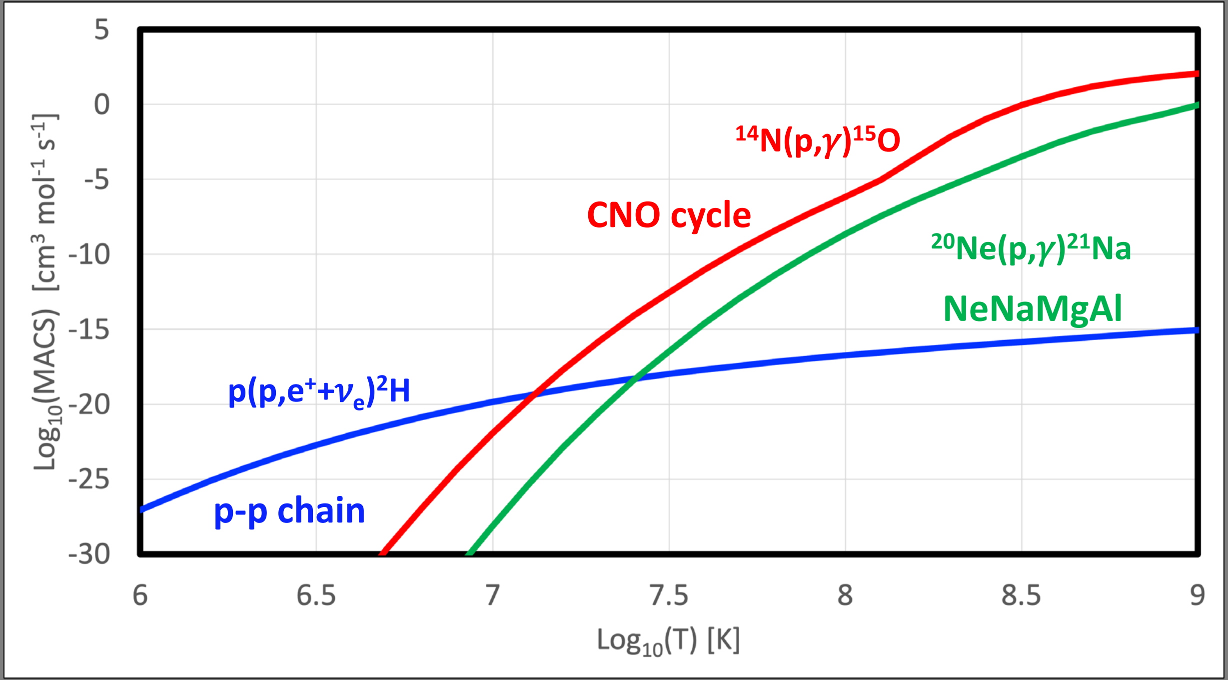


$L \propto M^3$
p(p,e⁺+νₑ)²H
p-p chain
Log10(MACS) [cm3 mol-1 s-1]
Log10(T) [K]
5
0
-5
-10
-15
-20
-25
-30
6
6.5
7
7.5
8
8.5
9

$$R_{ij} = \frac{y_i y_j}{1+\delta_{ij}} N_A^2 \rho^2 < \sigma v >_{ij}$$



$$R_{ij} = \frac{y_i y_j}{1 + \delta_{ij}} N_A^2 \rho^2 < \sigma v >_{ij}$$



The P-P chain

$4\mathrm{p} \rightarrow {}^4\mathrm{He}\ \ [26.73\ \mathrm{MeV}]$ $\quad E_{\mathrm{H}\rightarrow\mathrm{He}} = 6.44 \times 10^{18}\ \mathrm{erg\ g^{-1}}$

Energy released by an Earthquake of magnitudo 5 on the Richter scale

$\mathrm{p(p, e^+ + \nu)^2H}$

15 MK – 1.442 MeV – **0.42 MeV(sp)**

$\mathrm{^2H(p, \gamma)^3He}$

1.6 MK – 5.49 MeV

$\mathrm{^3He(^3He, 2p)^4He}$

8 MK – 12.96 MeV

$\mathrm{^3He(^4He)^7Be}$

15 MK – 1.587 MeV

$\mathrm{^7Be(e^-, e^+ + \nu)^7Li}$

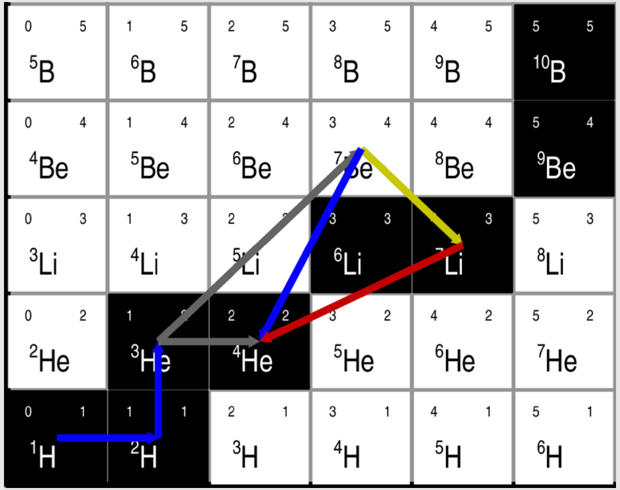
$\tau \simeq 30$ yr - 0.862 MeV – **1.244 MeV (Sp+Li)**

$\mathrm{^7Li(p, \gamma)^8Be \rightarrow 2\ ^4He}$

4 MK – 17.347 MeV

$\mathrm{^7Be(p, \gamma)^8B \rightarrow 2\ ^4He}$

20 MK -18.209 MeV – **14.06 MeV (sp)**



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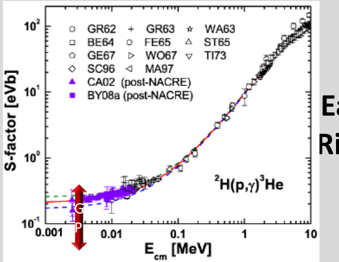
$4p \rightarrow {}^4\mathrm{He}\ \ [26.73\ \mathrm{MeV}]$ $\qquad E_{H\rightarrow He} = 6.44 \times 10^{18}\ \mathrm{erg\ g^{-1}}$



Earthquake of Richter scale

$p(p, e^+ + \nu)^2H$

15 MK – 1.442 MeV – **0.42 MeV(sp)**

$^2H(p, \gamma)^3He$

1.6 MK – 5.49 MeV

$^3He(^3He, 2p)^4He$

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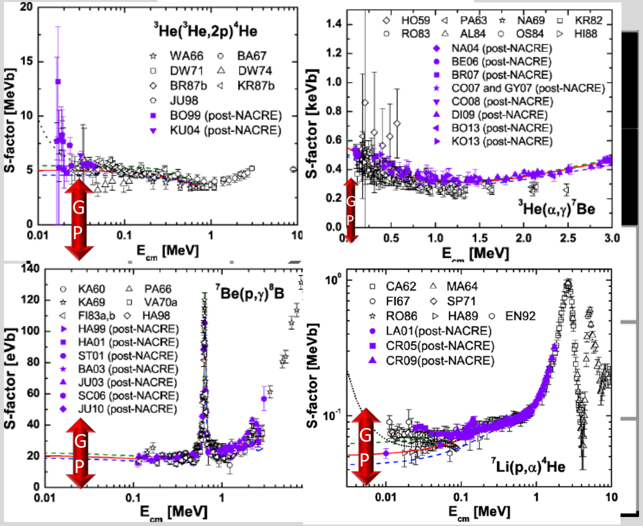


CNO cycle

$$T \sim 3 - 5 \cdot 10^7 \text{ K} \quad \rho \sim 1 - 10 \text{ gcm}^{-3}$$

CN

$^{12}C(p,\gamma)^{13}N$

$^{13}N(\beta^+,\nu)^{13}C$

$^{13}C(p,\gamma)^{14}N$

$^{14}N(p,\gamma)^{15}O$ ← slowest

$^{15}O(\beta^+,\nu)^{15}N$

$^{15}N(p,\alpha)^{12}C$

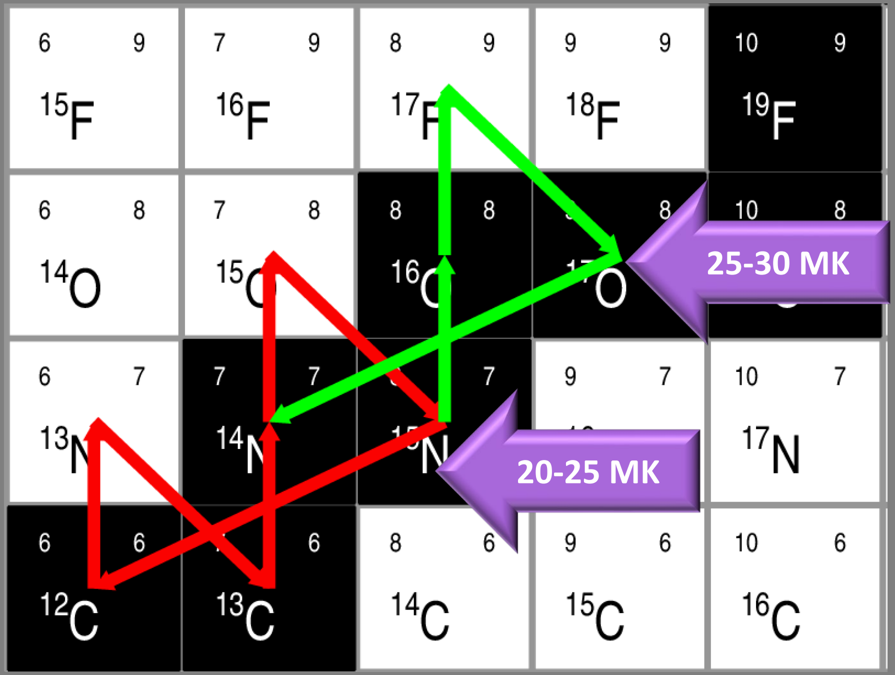
NO

$(p,\gamma)^{16}O$

$^{16}O(p,\gamma)^{17}F$

$^{17}F(\beta^+,\nu)^{17}O$

$^{17}O(p,\alpha)^{14}N$



CNO cycle

$$T \sim 3 - 5 \cdot 10^7 \ \mathrm{K} \quad \rho \sim 1 - 10 \ \mathrm{g cm^{-3}}$$

CN

$^{12}C(p,\gamma)^{13}N$

$^{13}N(\beta^+,\nu)^{13}C$

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$^{15}N(p,\alpha)^{12}C$

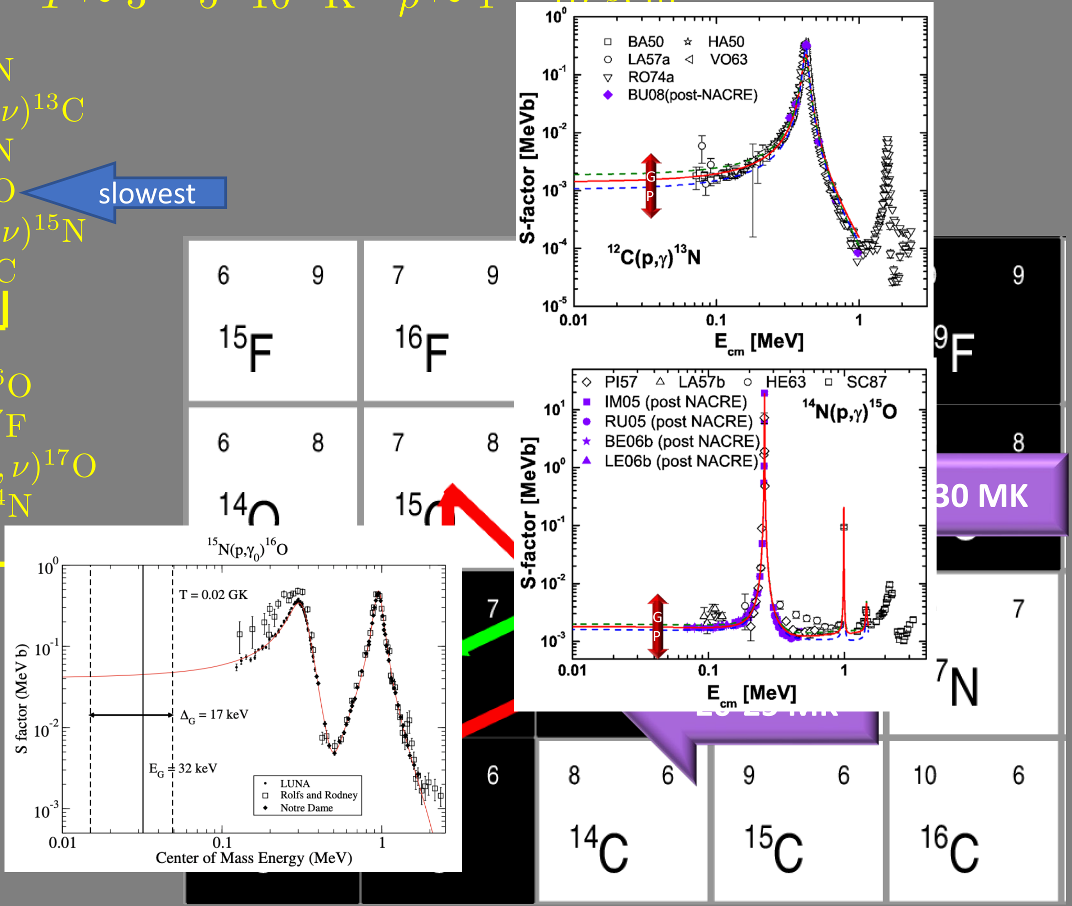
NO

$(p,\gamma)^{16}O$

$^{16}O(p,\gamma)^{17}F$

$^{17}F(\beta^+,\nu)^{17}O$

$^{17}O(p,\alpha)^{14}N$



CNO cycle

$$\mathrm{T} > 20\ \mathrm{MK} \qquad \rho \sim 1 - 10\ [\mathrm{gr\ cm^{-3}}]$$

$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ slowest reaction

(measured by LUNA/LENA)

CNO processed material: $^{12}\mathrm{C}\downarrow \quad ^{14}\mathrm{N}\uparrow \quad ^{16}\mathrm{O}\downarrow$

Typical equilibrium ratios:

$$\frac{^{12}C}{^{13}C} \sim 4 \qquad \frac{^{14}N}{^{15}N} \sim 45000 \qquad \frac{^{16}O}{^{17}O} \sim 170$$

$$\frac{N}{C} \sim 140 \qquad \frac{C}{O} \sim 0.2$$

NeNa & MgAl (chains or cycles?)

T > 55 MK

NeNa

$^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}$

$^{21}\mathrm{Na}(\beta^+,\nu)^{21}\mathrm{Ne}$

$^{21}\mathrm{Ne}(p,\gamma)^{22}\mathrm{Na}$

$^{22}\mathrm{Na}(\beta^+,\nu)^{22}\mathrm{Ne}$

$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$

$^{23}\mathrm{N}(p,\alpha)^{20}\mathrm{Ne}$

$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$

MgAl

$^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$

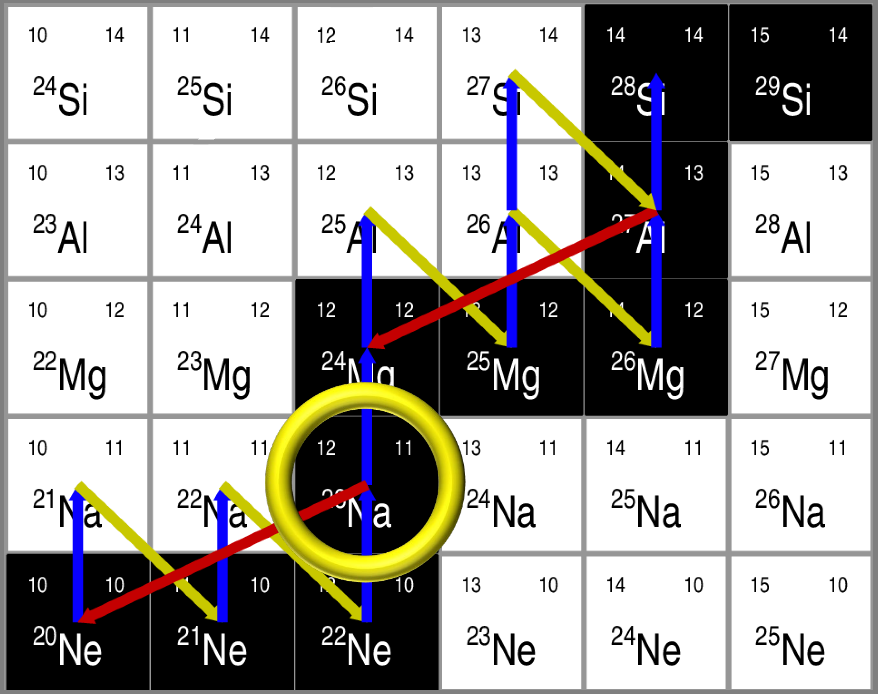
$^{25}\mathrm{Al}(\beta^+,\nu)^{25}\mathrm{Mg}$

$^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$

$^{26}\mathrm{Al}(\beta^+,\nu)^{26}\mathrm{Mg}$

$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$

$^{27}\mathrm{Al}(p,\alpha)^{24}\mathrm{Mg}$



NeNa & MgAl (chains or cycles?)

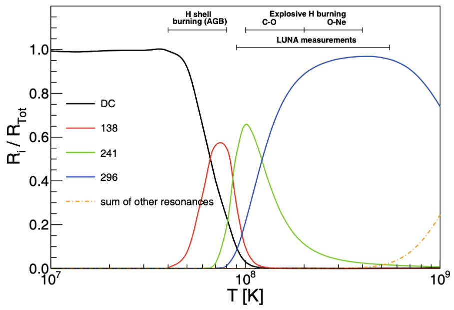


Fig. 12. Fractional contributions to the reaction rate of ^{23}Na $(p,\gamma)^{24}$Mg, as a function of temperature, see text for details.

Boeltzig + Eur. Phys. J. A (2016) 52: 75

> 55 MK

NeNa

$^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$

MgAl

$^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}$

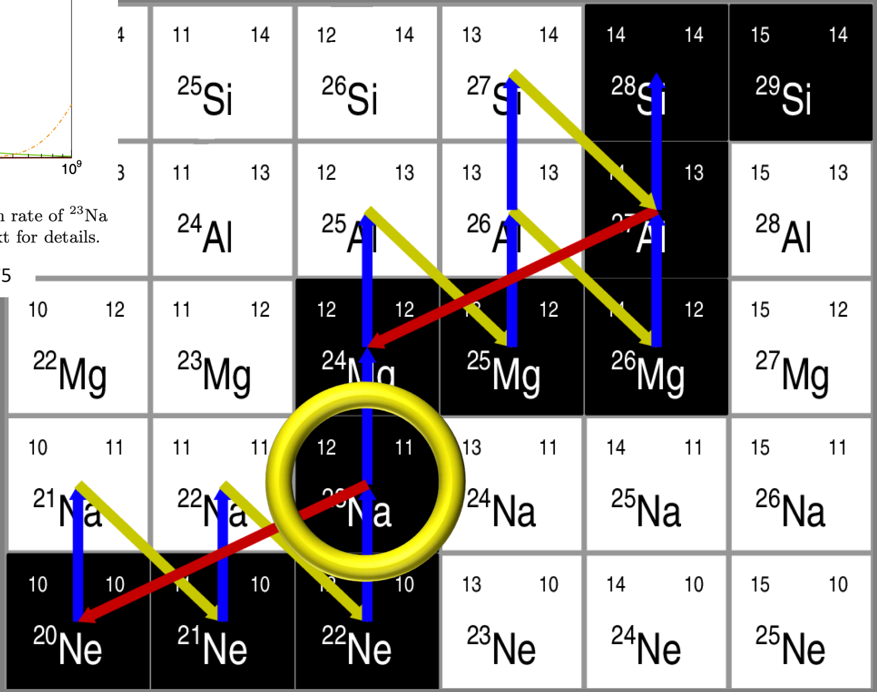
$^{25}\mathrm{Al}(\beta^+,\nu)^{25}\mathrm{Mg}$

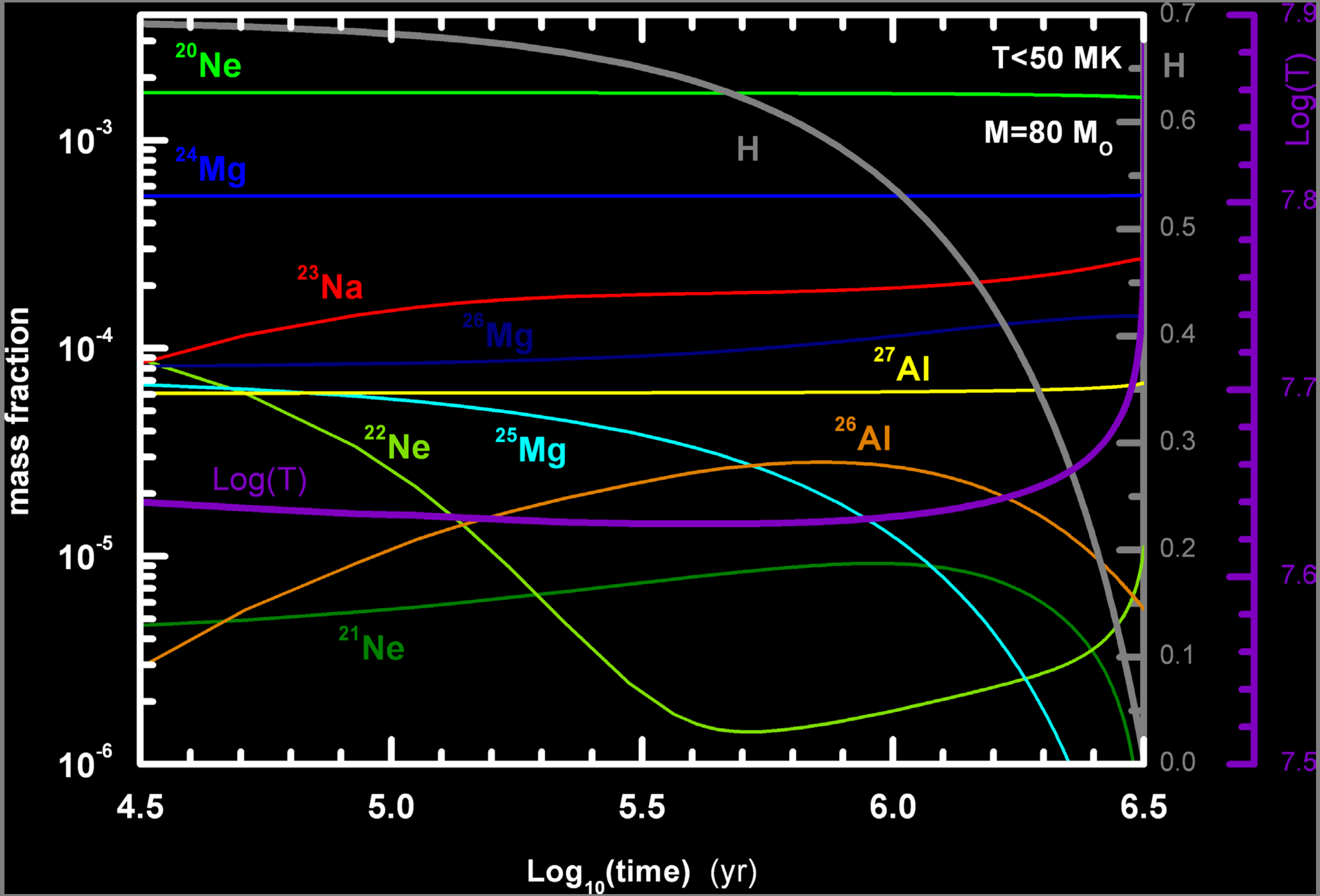
$^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$

$^{26}\mathrm{Al}(\beta^+,\nu)^{26}\mathrm{Mg}$

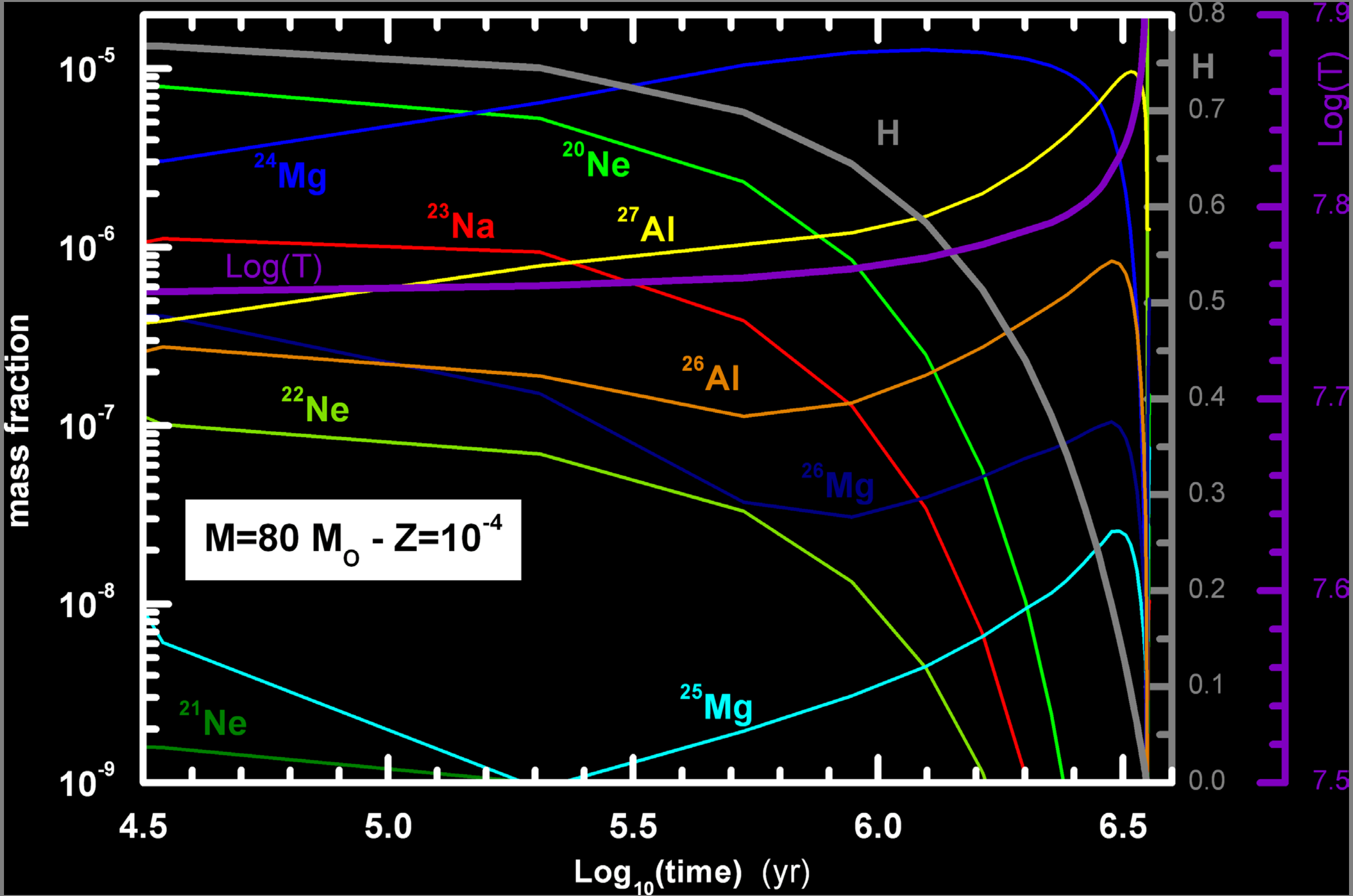
$^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$

$^{27}\mathrm{Al}(p,\alpha)^{24}\mathrm{Mg}$





mass fraction
10^-3
10^-4
10^-5
10^-6
20Ne
24Mg
23Na
26Mg
27Al
22Ne
25Mg
26Al
21Ne
Log(T)
H
T<50 MK
M=80 Mo
4.5
5.0
5.5
6.0
6.5
Log10(time) (yr)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
7.9
7.8
7.7
7.6
7.5



M=80 M_O - Z=10^-4
mass fraction
10^-5
10^-6
10^-7
10^-8
10^-9
Log_10(time) (yr)
4.5
5.0
5.5
6.0
6.5
H
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Log(T)
7.9
7.8
7.7
7.6
7.5
24Mg
20Ne
H
23Na
27Al
Log(T)
26Al
22Ne
26Mg
25Mg
21Ne

NeNa & MgAl (chains or cycles?)

T > 55 MK

Gratton+, A&A Rev. 27,8 (2019)

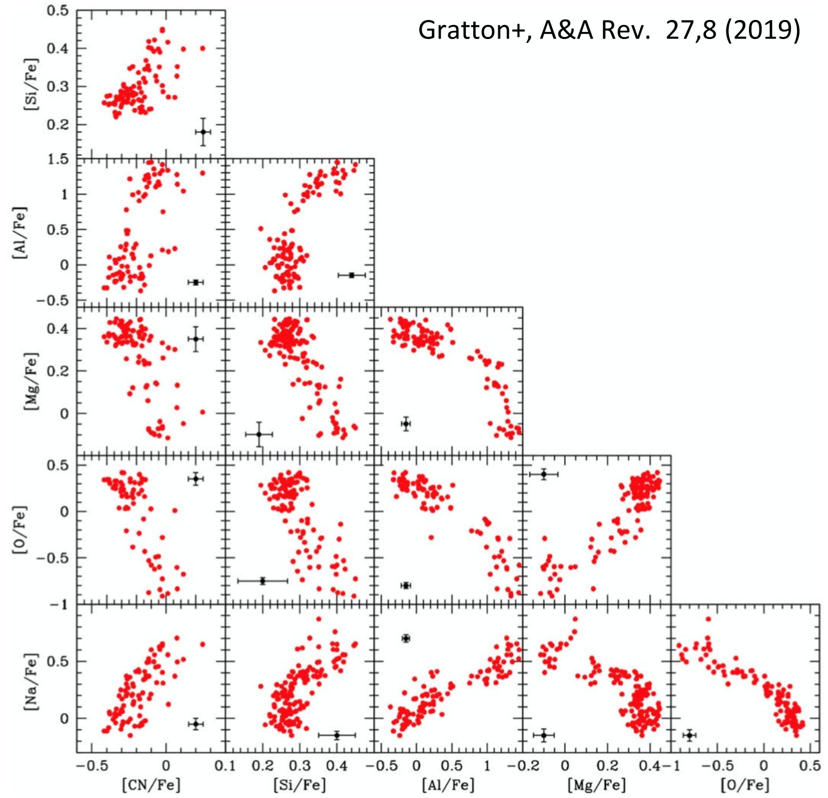
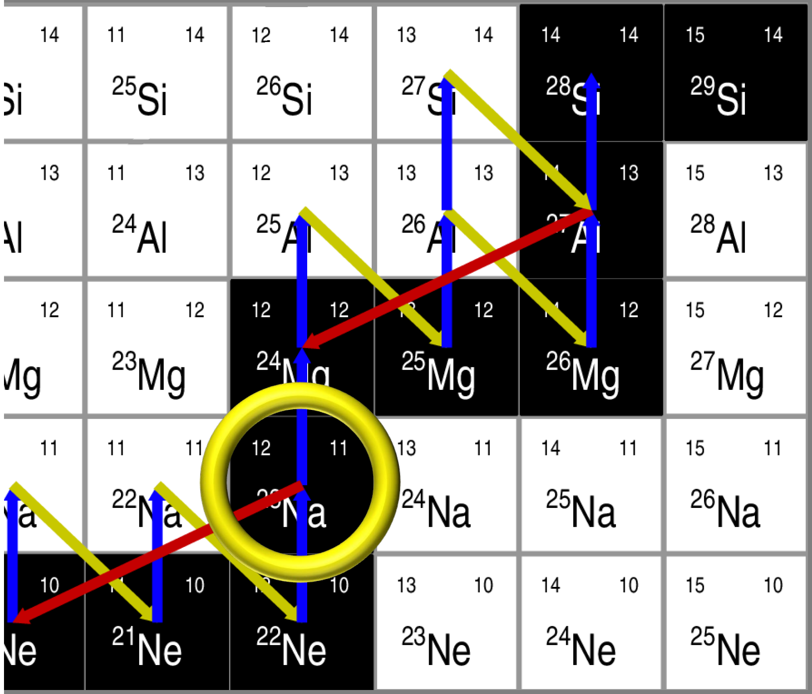
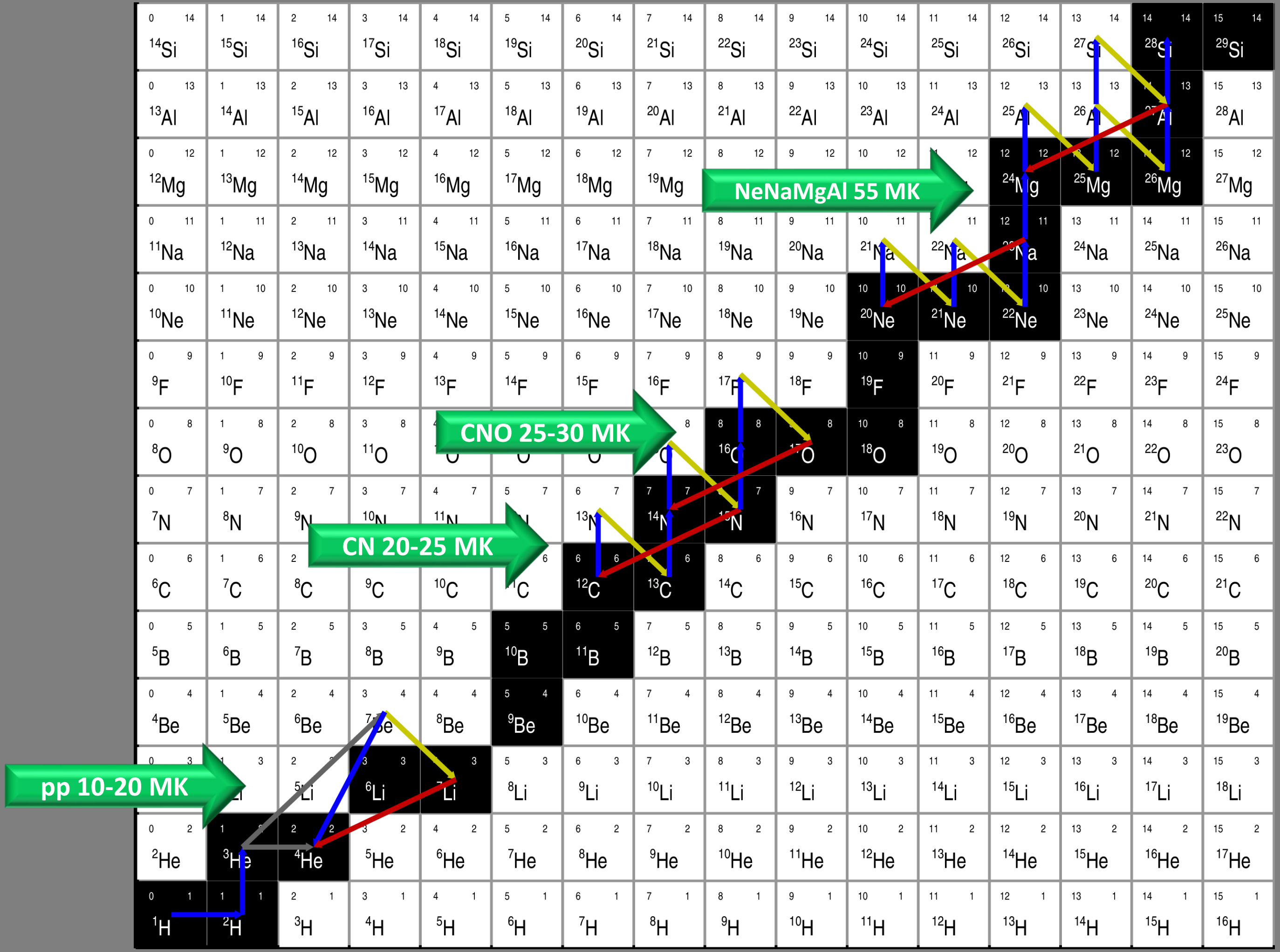
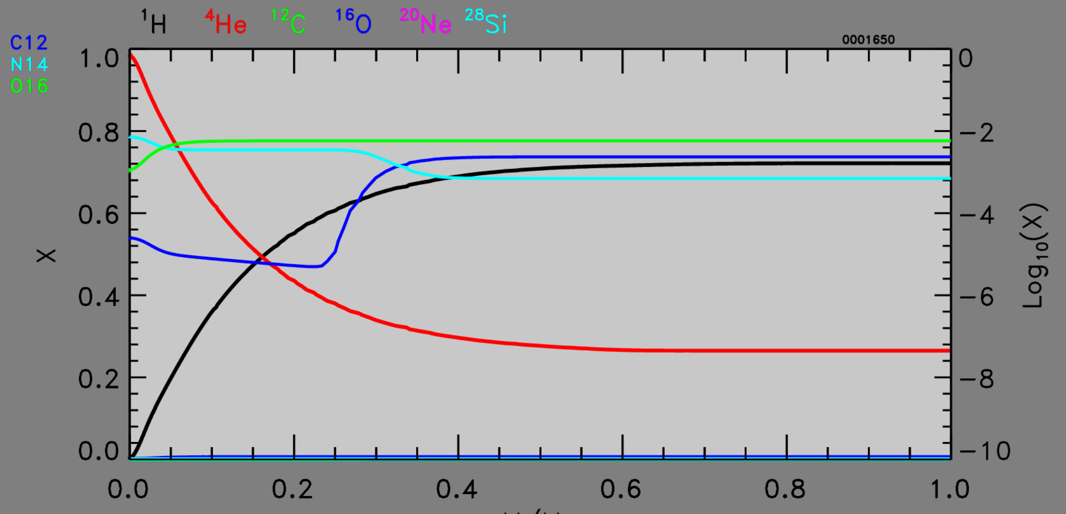


Fig. 2 Run of abundance ratios for light elements in RGB stars in NGC 2808. O, Na, Si, and Mg are from Carretta (2015), Al and CN abundances from Carretta et al. (2018). The figure is adapted from the invited review by Carretta (2016)

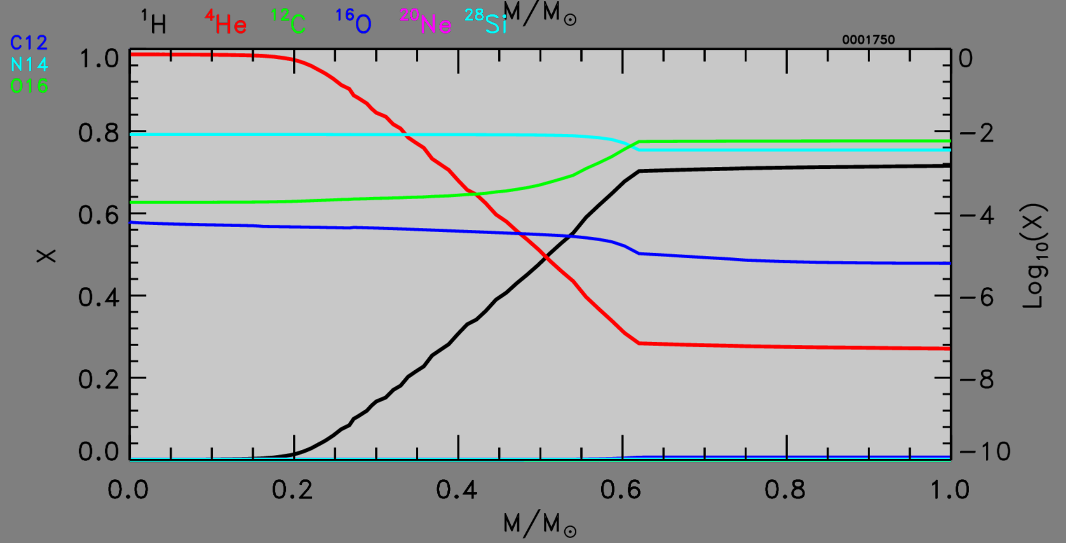



NeNaMgAl 55 MK
CNO 25-30 MK
CN 20-25 MK
pp 10-20 MK

M < 1.3 M$_\odot$
Radiative core
PP chain



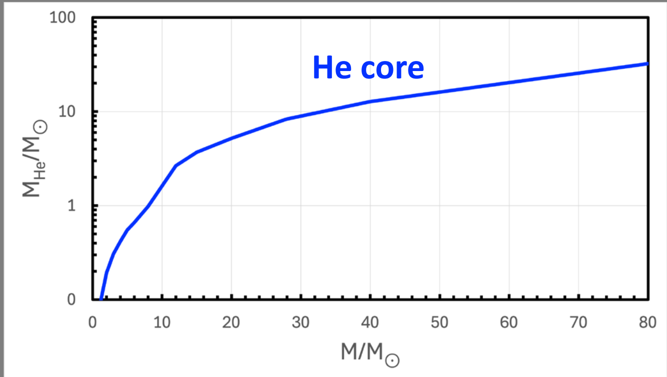
M > 1.3 M$_\odot$
convective core
CNO cycle



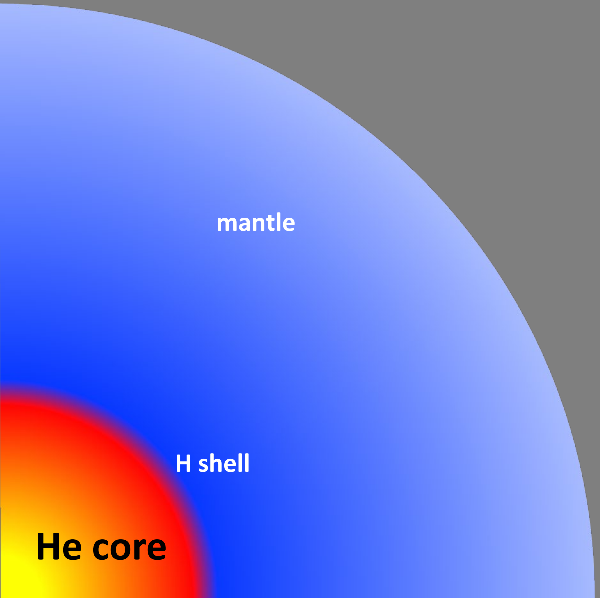
Central H exhaustion

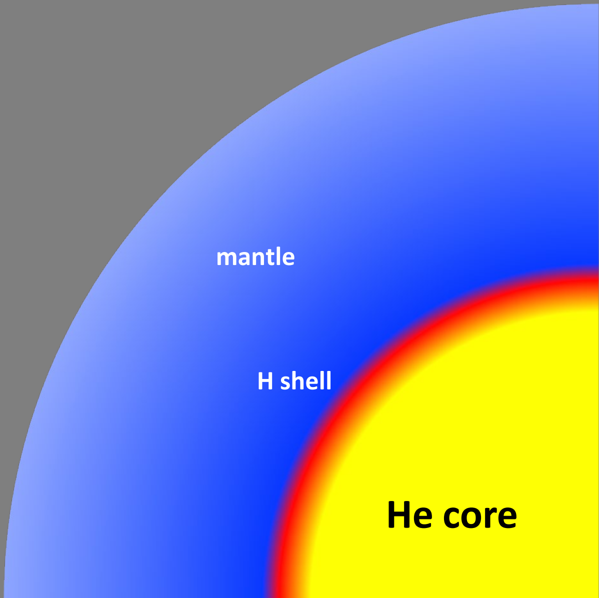
monotonic family of stars

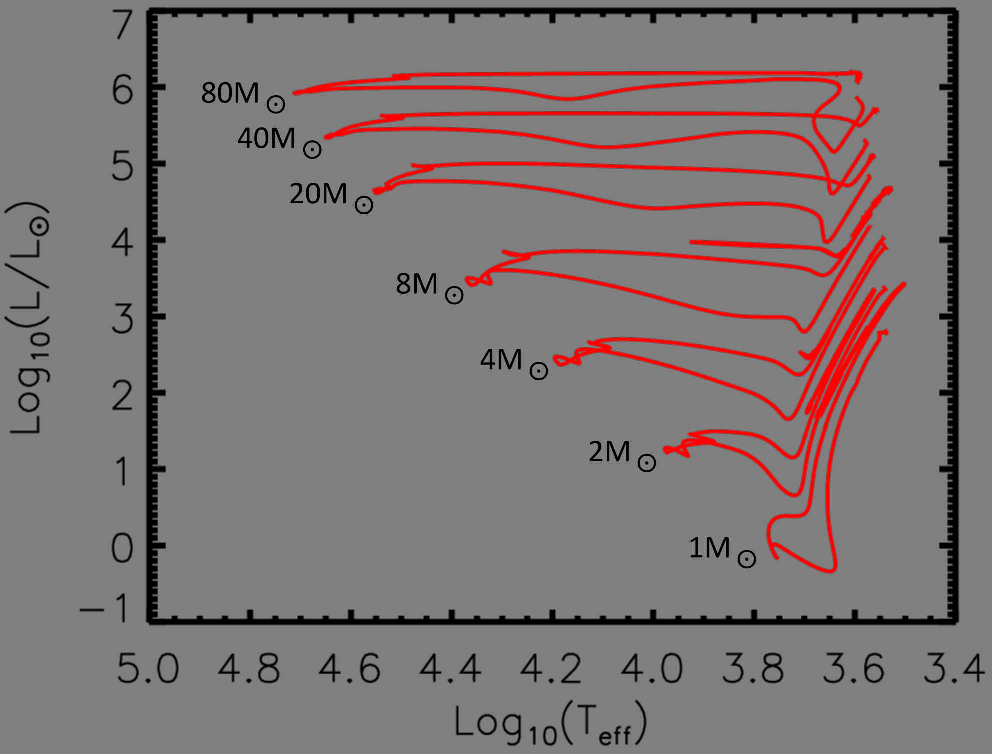
$M < 1.3\ M_\odot$
Radiative core
PP chain



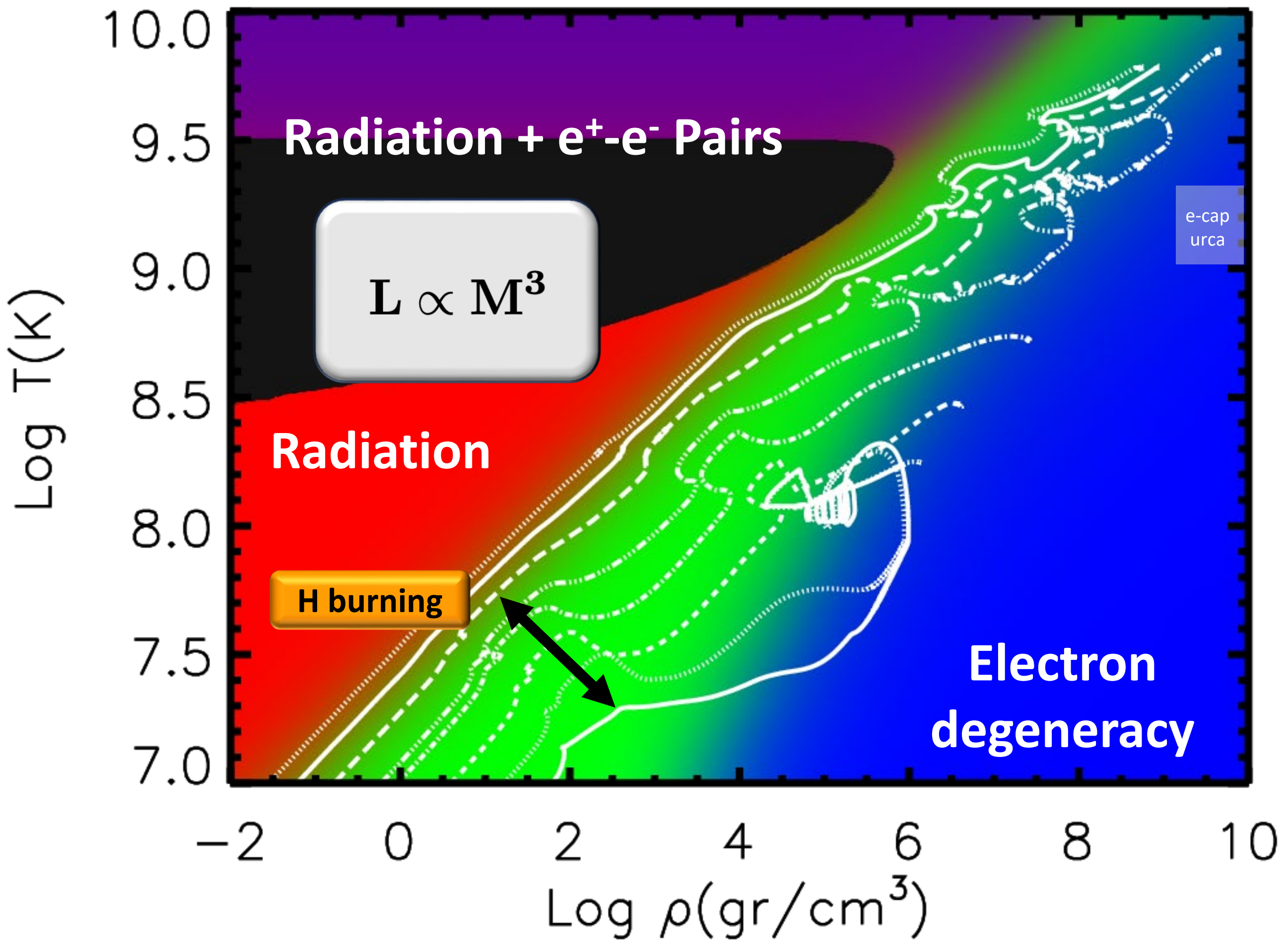
$M > 1.3\ M_\odot$
convective core
CNO cycle



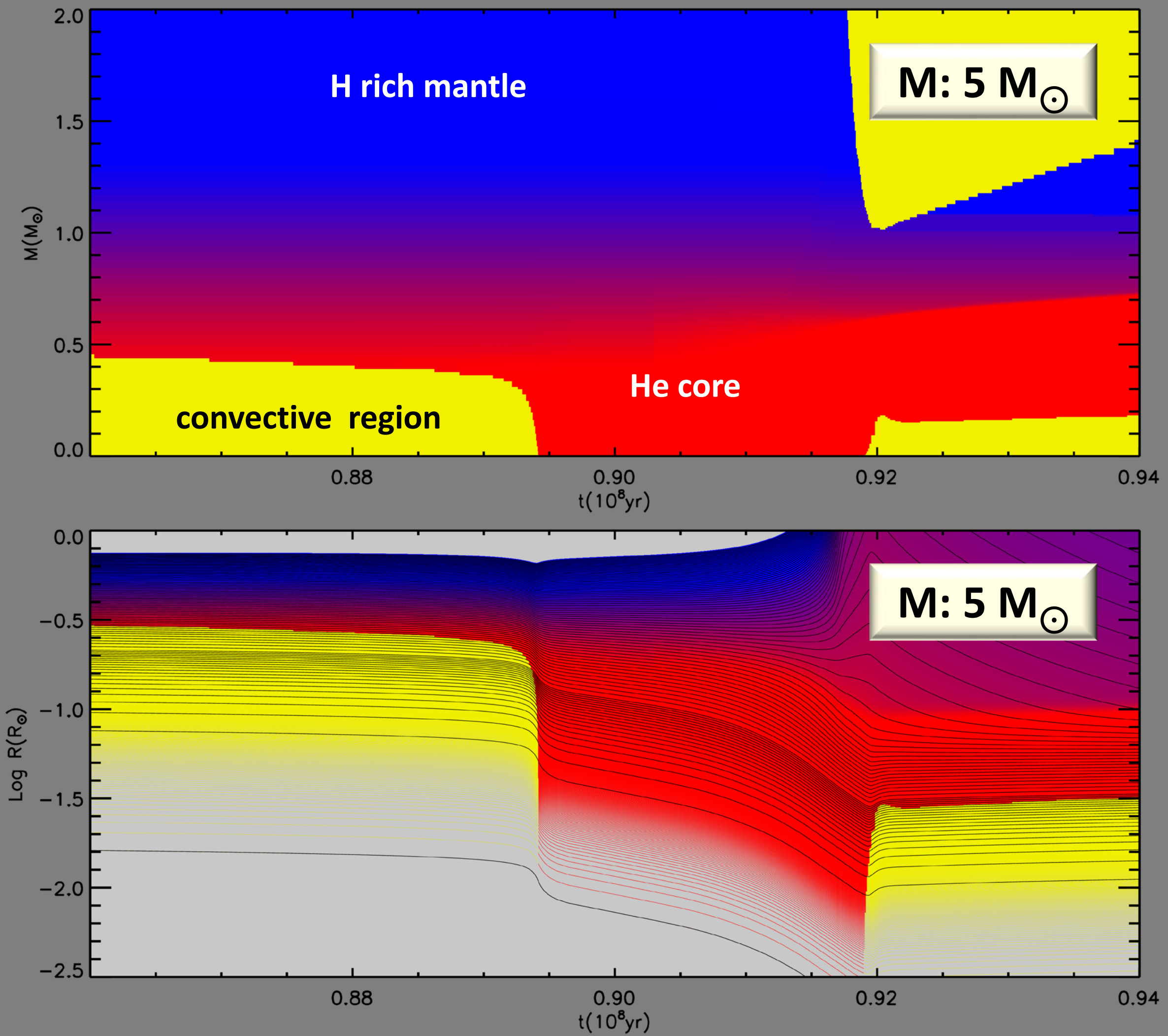




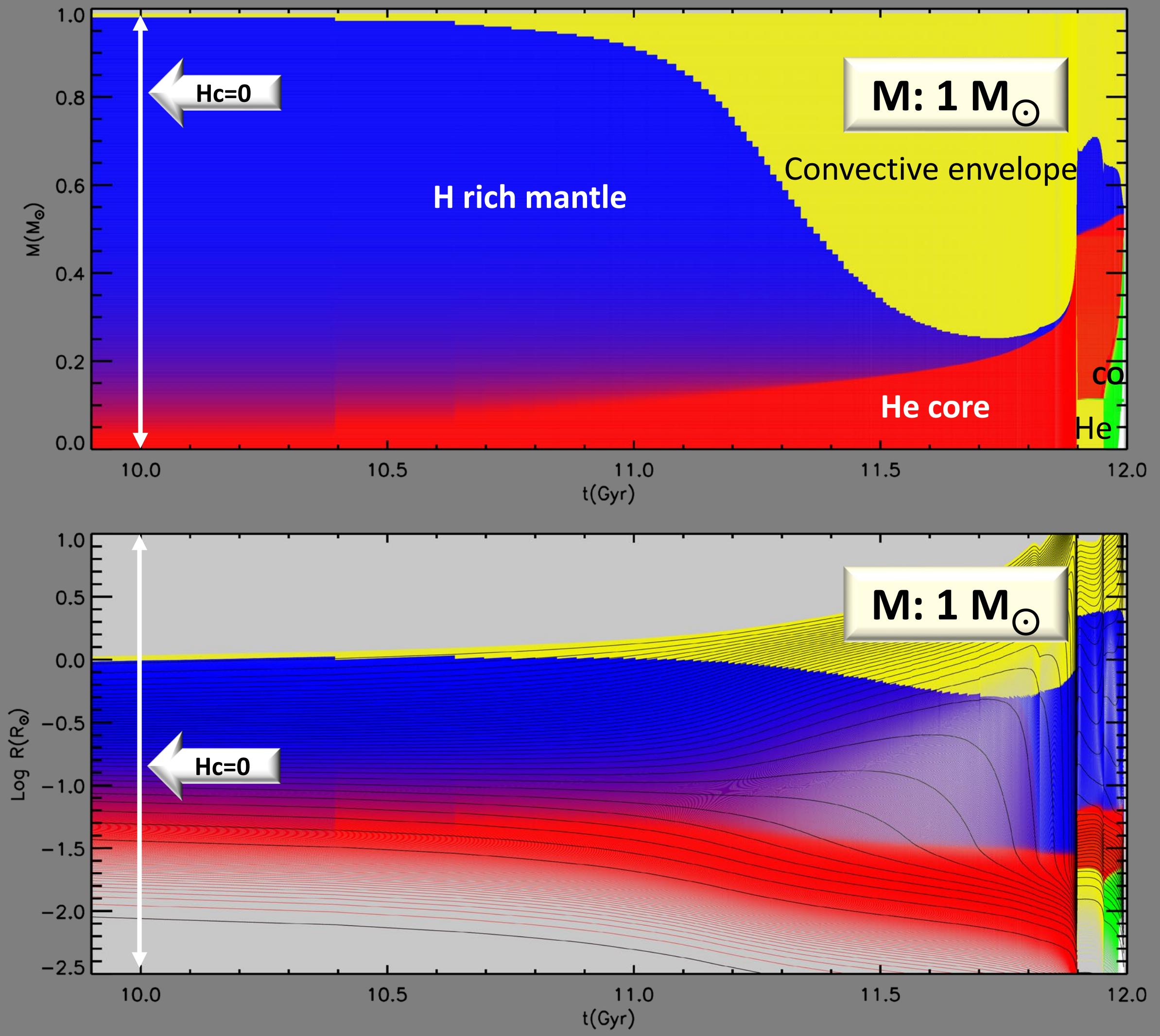
80M☉
40M☉
20M☉
8M☉
4M☉
2M☉
1M☉
Log10(L/L☉)
Log10(Teff)

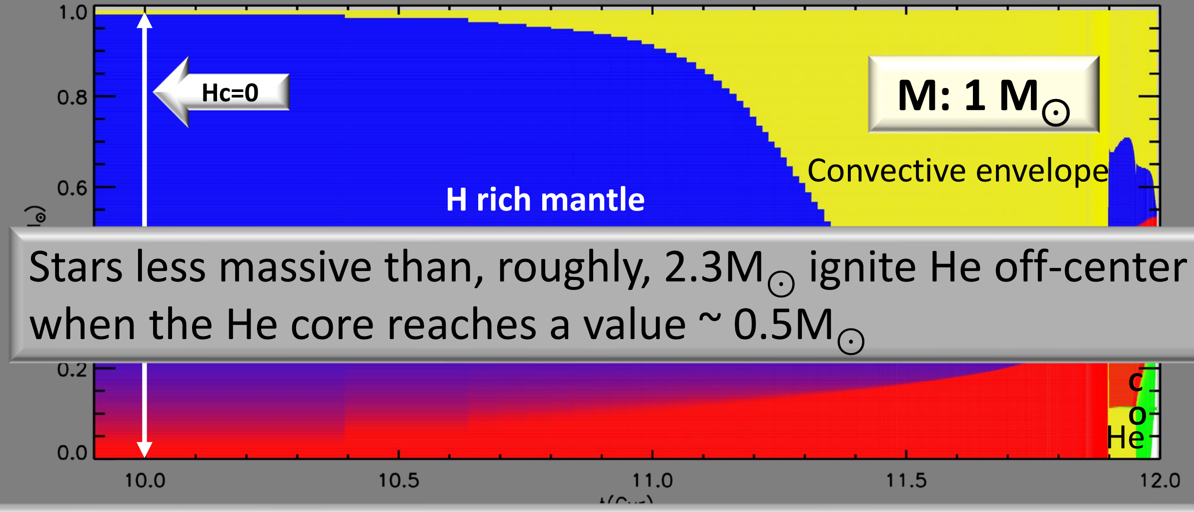


Radiation + e+-e- Pairs
L ∝ M³
Radiation
H burning
Electron degeneracy
e-cap
urca
Log T(K)
Log ρ(gr/cm³)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10



2.0
1.5
1.0
0.5
0.0
M(M⊙)
H rich mantle
M: 5 M⊙
convective region
He core
0.88
0.90
0.92
0.94
t(10⁸yr)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Log R(R⊙)
M: 5 M⊙
0.88
0.90
0.92
0.94
t(10⁸yr)


M: 1 M☉
Hc=0
H rich mantle
Convective envelope
He core
CO
He
M(M☉)
t(Gyr)
1.0
0.8
0.6
0.4
0.2
0.0
10.0
10.5
11.0
11.5
12.0
M: 1 M☉
Hc=0
Log R(R☉)
t(Gyr)
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
10.0
10.5
11.0
11.5
12.0

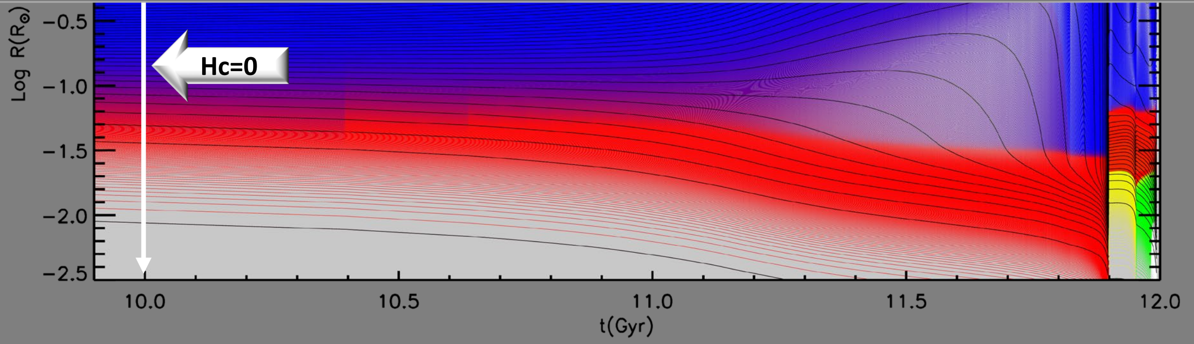


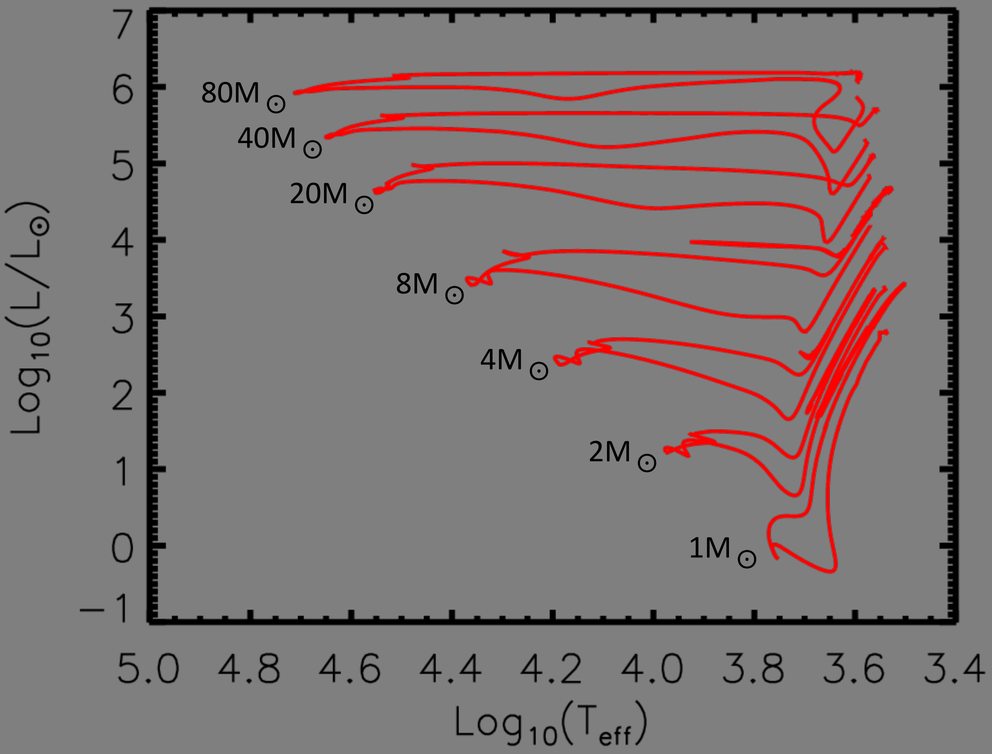
Stars less massive than, roughly, $2.3 M_\odot$ ignite He off-center when the He core reaches a value ~ $0.5 M_\odot$

All stars are able to lift the electron degeneracy because:

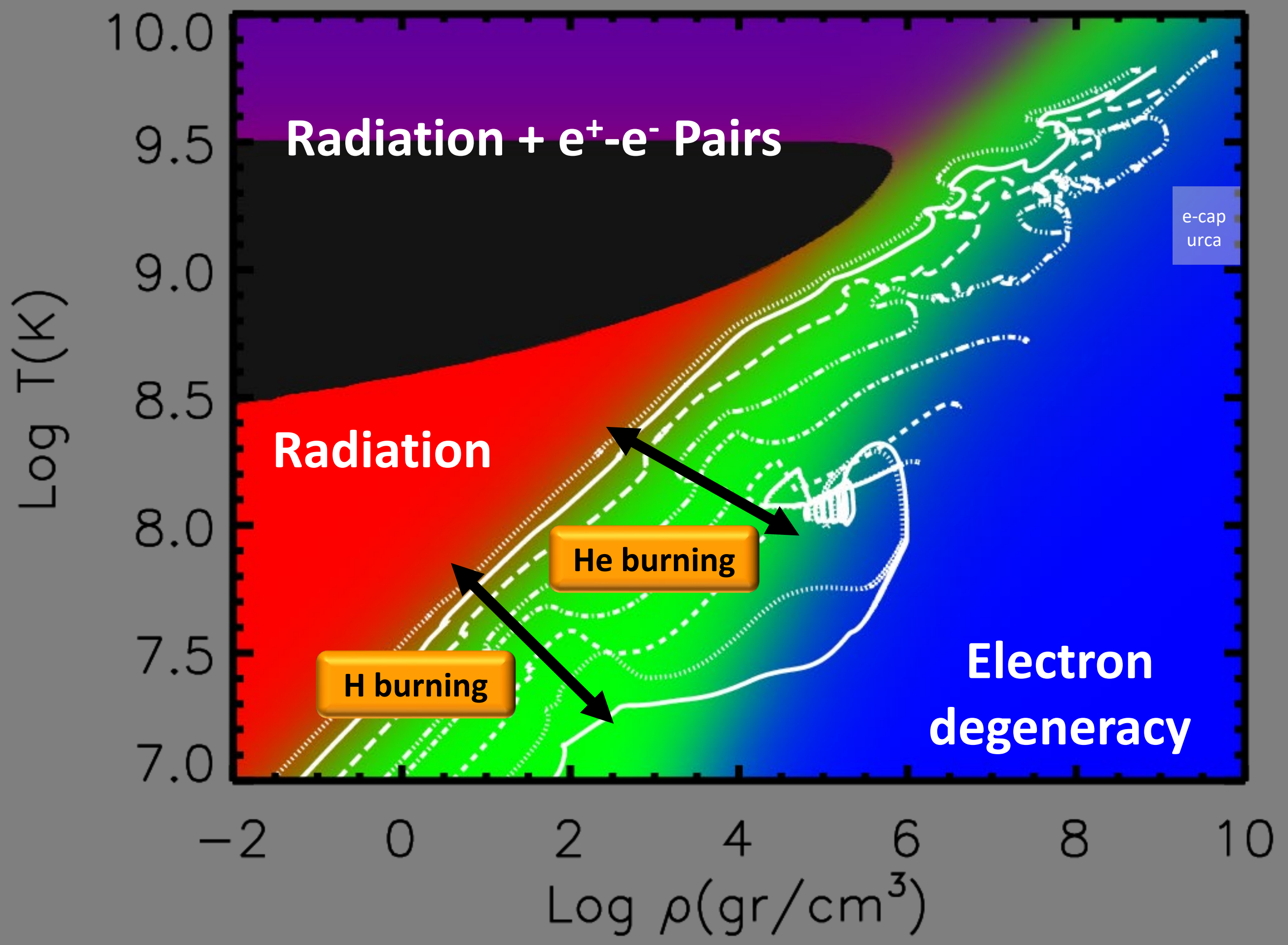
Energy required to lift the degeneracy at $Log_{10}(\rho)=6$ => $5\ 10^{22}$ [erg/cm^3]

Energy provided by the 3α at $Log_{10}(\rho)=6$ => $8\ 10^{23}$ [erg/cm^3]





80M ⊙
40M ⊙
20M ⊙
8M ⊙
4M ⊙
2M ⊙
1M ⊙
$\mathrm{Log}_{10}(L/L_\odot)$
$\mathrm{Log}_{10}(T_{\mathrm{eff}})$
7
6
5
4
3
2
1
0
−1
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4



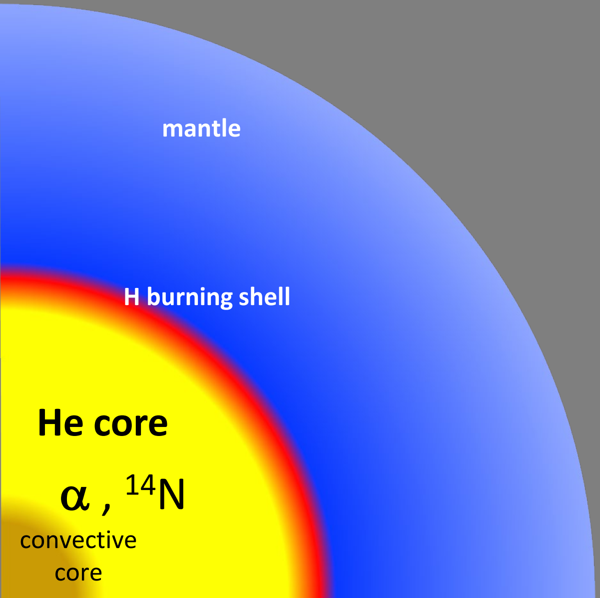
Radiation + e⁺-e⁻ Pairs
Radiation
He burning
H burning
Electron degeneracy
e-cap urca
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Log T(K)
−2
0
2
4
6
8
10
Log ρ(gr/cm³)

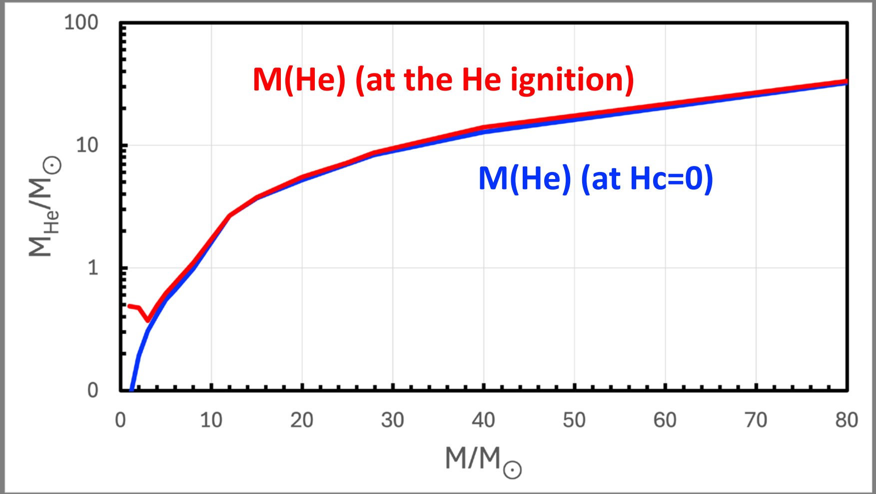
He burning

The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

Central He burning always occurs in a convective environment

$$3\alpha \rightarrow^{12}\mathrm{C} \qquad {}^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$$





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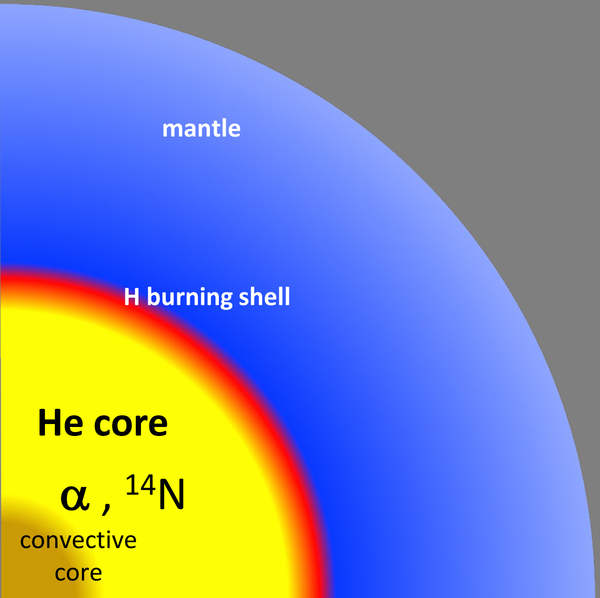
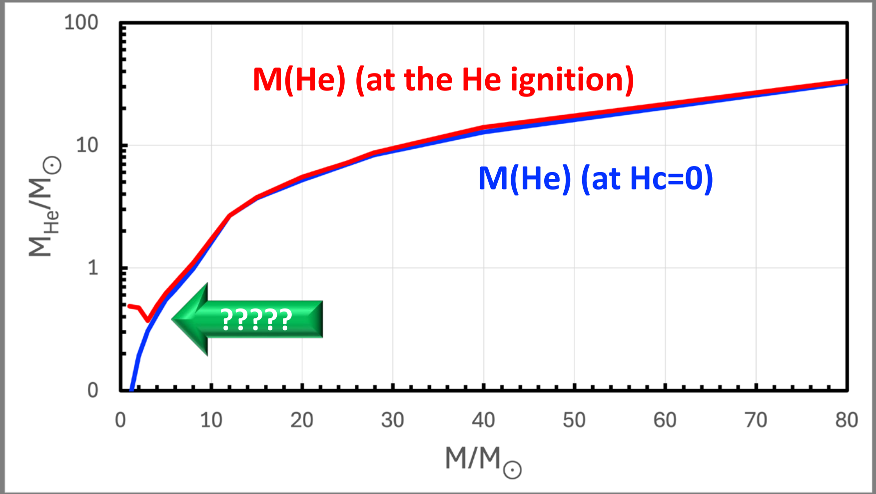




He burning

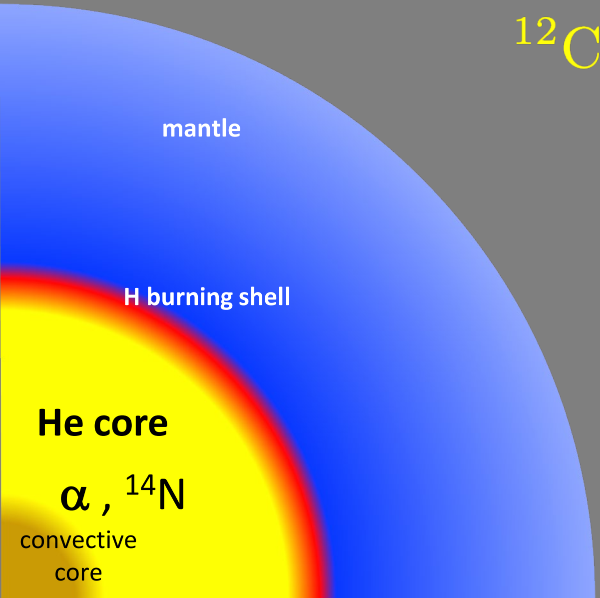
The key parameter that drives the evolution in He burning is the He core mass and NOT the total mass

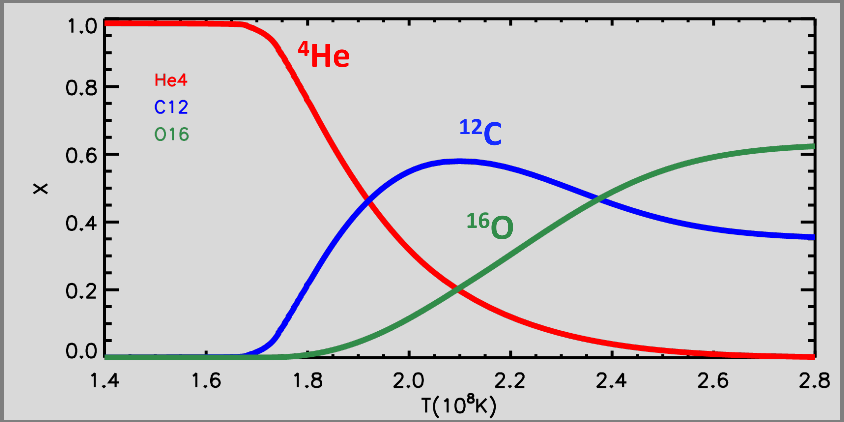
Central He burning always occurs in a convective environment

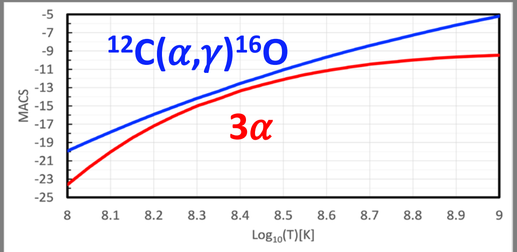
$$T \sim 1.5 - 3.5 \cdot 10^8 \text{ K} \quad \rho \sim 0.2 - 4 \cdot 10^3 \text{ gcm}^{-3}$$

$$4\,\alpha \rightarrow {}^{16}\text{O} \qquad \mathbf{\Delta M = 4 \times 4.0026 - 15.9949 = 0.015\ MeV} \qquad E_{nuc} = 8.70 \cdot 10^{17}\ \text{erg/g}$$

$$3\alpha \rightarrow {}^{12}\text{C}$$
$$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$$







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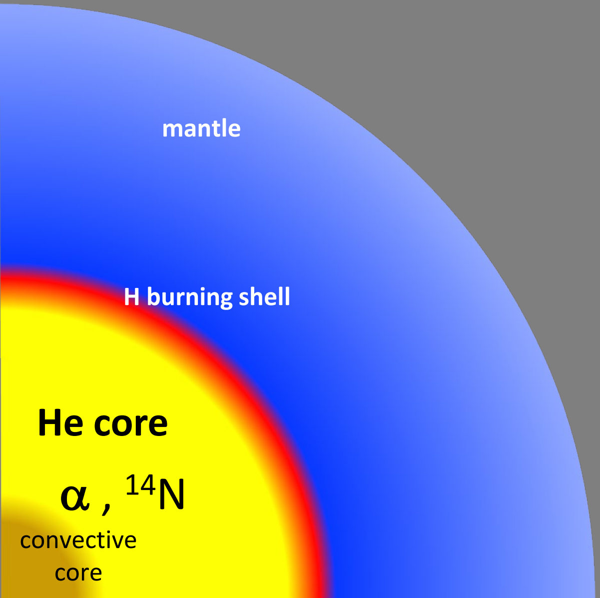

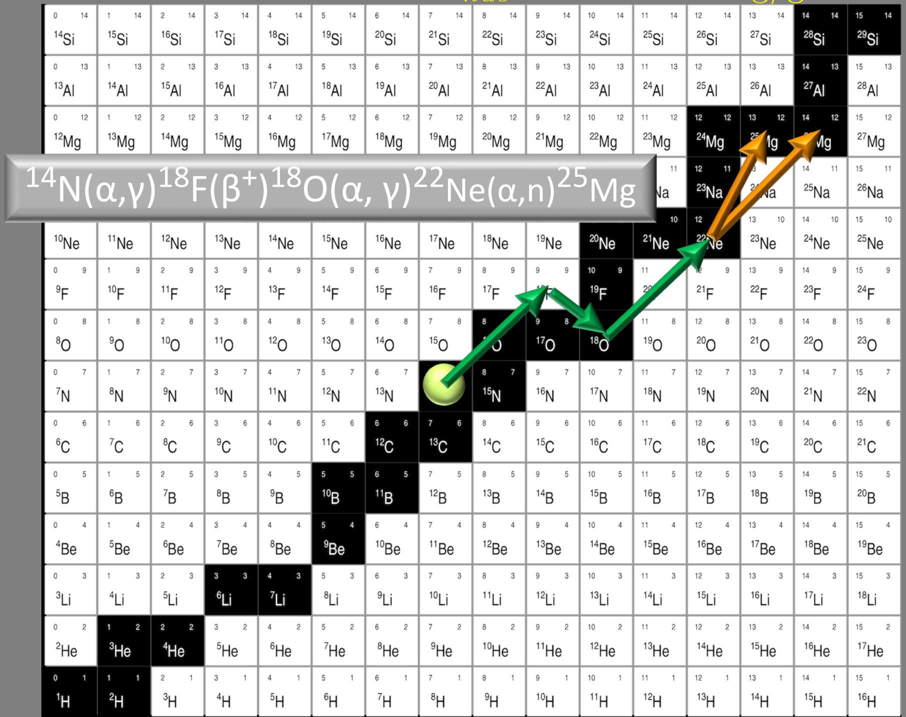

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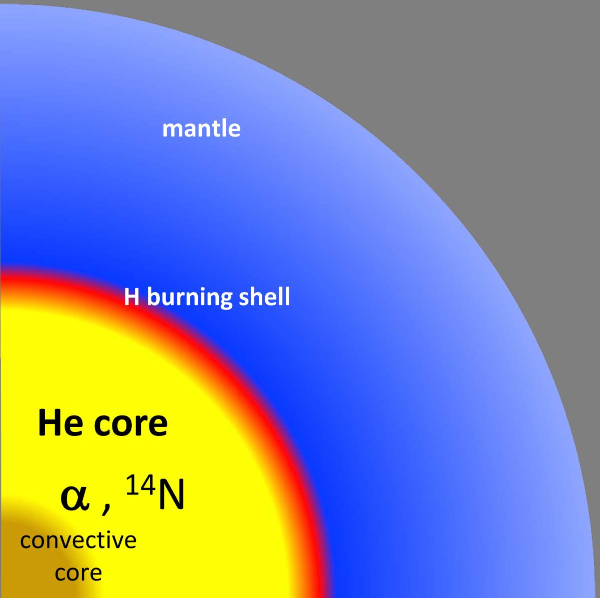
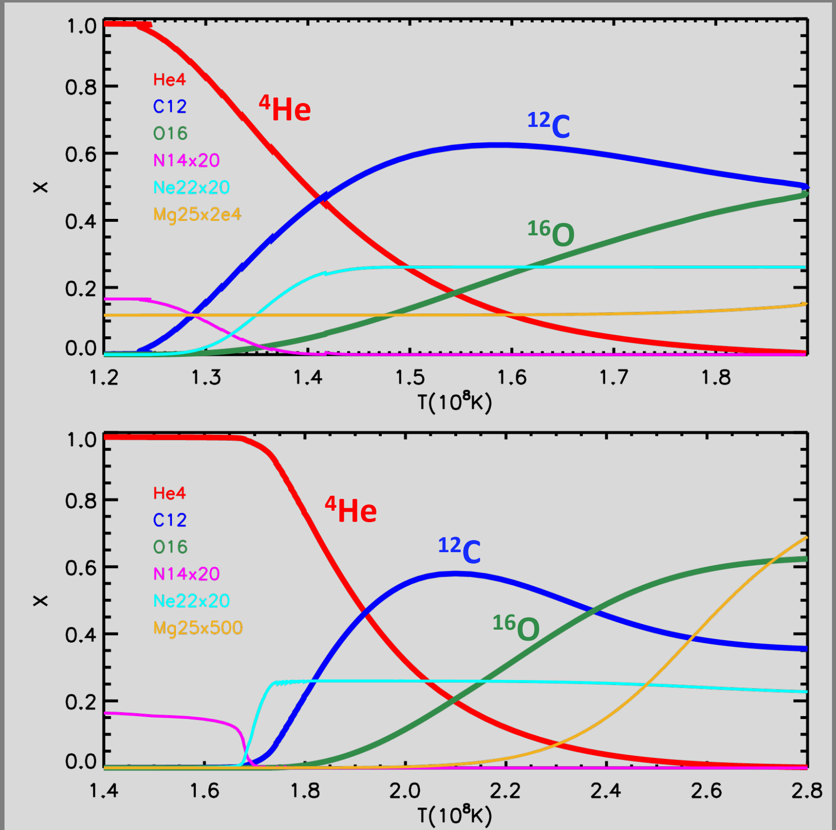
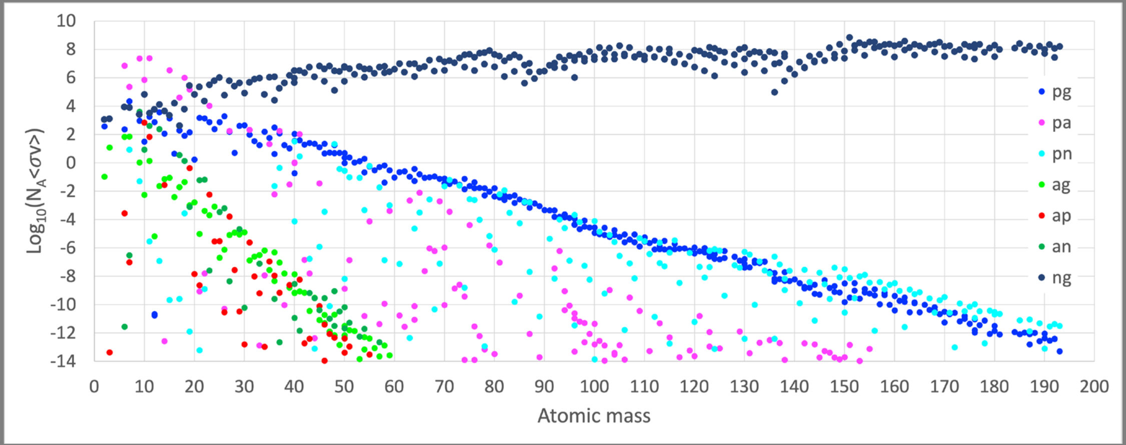
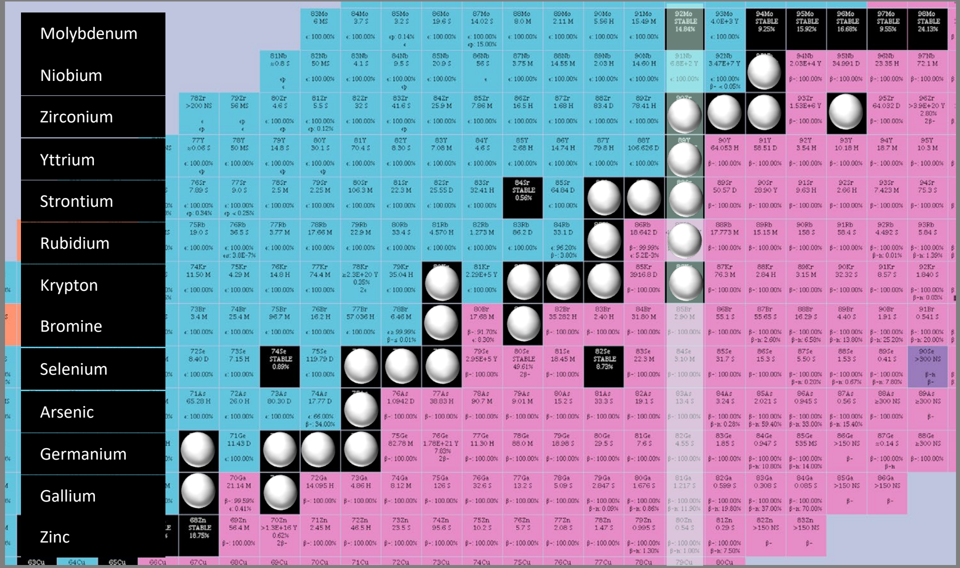








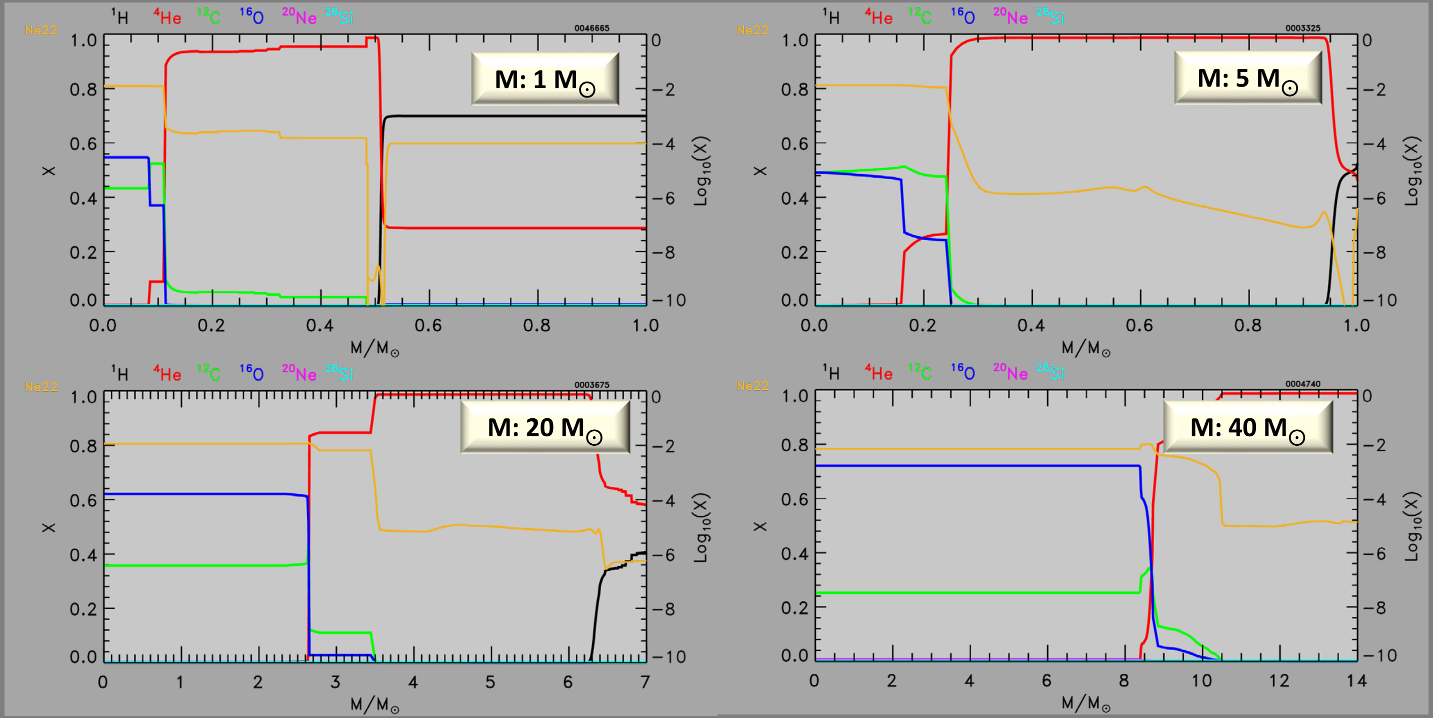
S-process nucleosynthesis (weak component)

He burning

At the central He exhaustion we do not have any more a monoparametric family of stars but a Bi-parametric family.

In fact from now on there are two leading parameters that drive the further evolution of each star:

the CO core mass and the amount of C left by the He burning.



He burning

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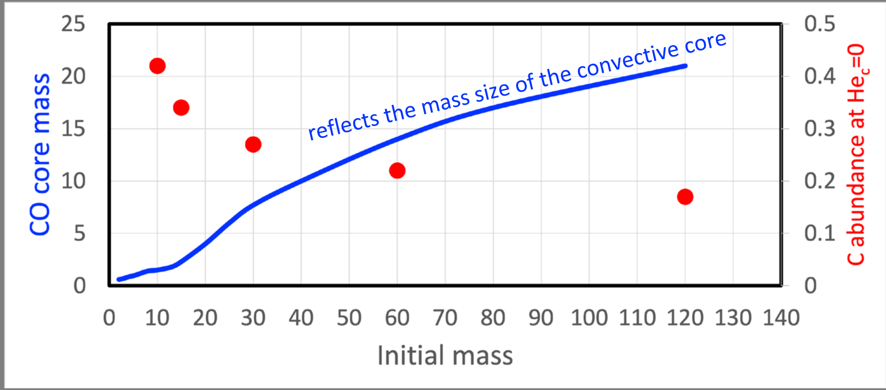
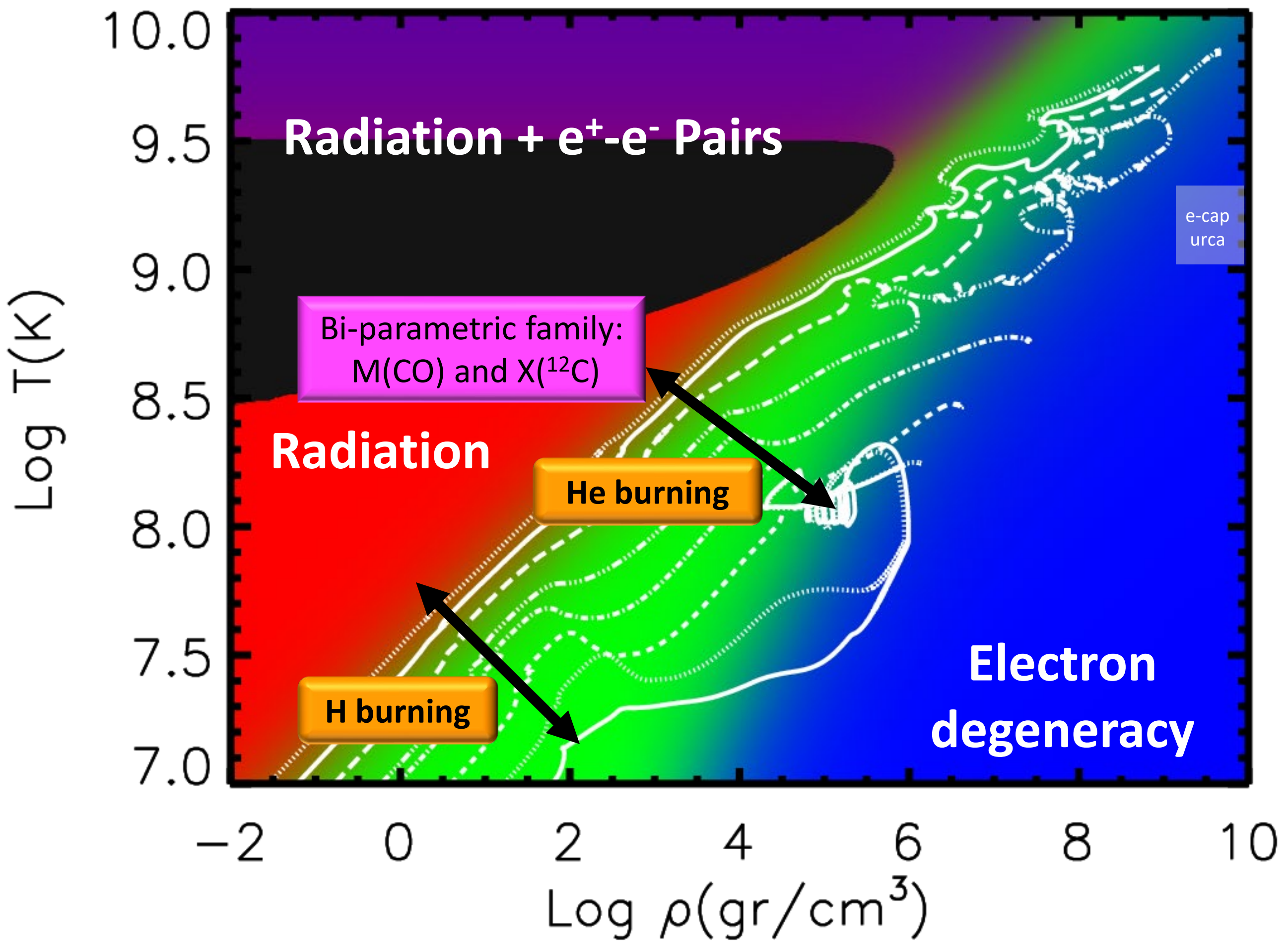




Radiation + e⁺-e⁻ Pairs
Bi-parametric family: M(CO) and X(¹²C)
Radiation
He burning
H burning
e-cap
urca
Electron degeneracy
10.0
9.5
9.0
8.5
8.0
7.5
7.0
Log T(K)
−2
0
2
4
6
8
10
Log ρ(gr/cm³)

Let us discuss the advanced phases of massive stars first

EVOLUTION OF MASSIVE STARS

R. J. TAYLER*
Princeton University Observatory

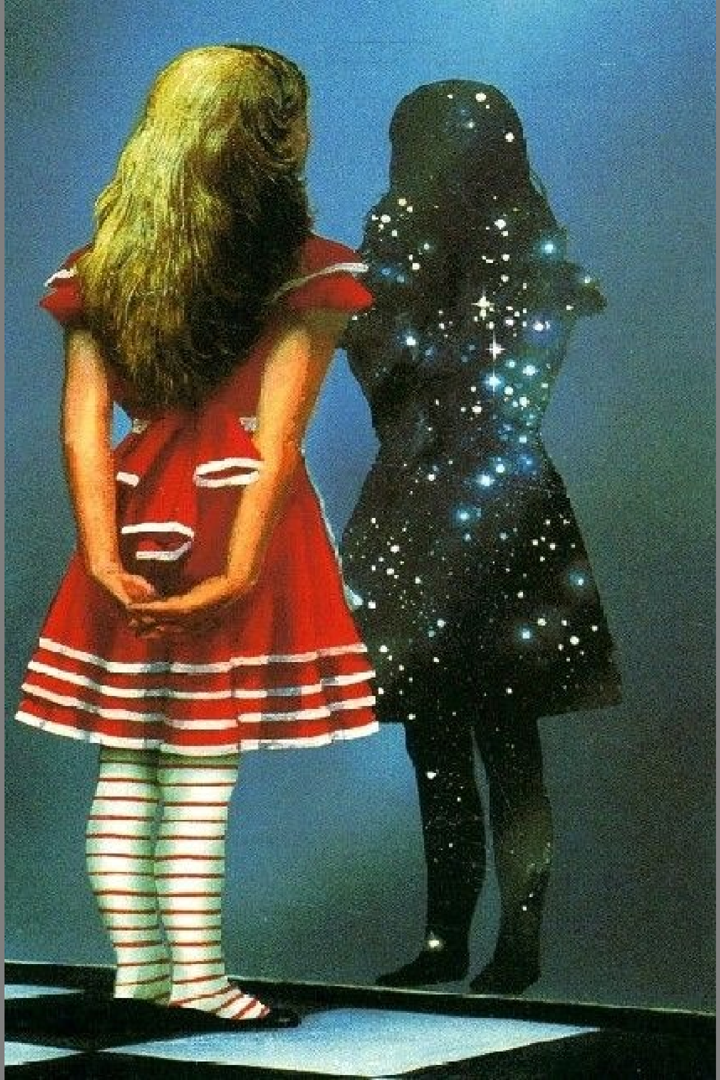
Received March 15, 1954

ABSTRACT

The evolution is considered of massive stars with opacity due to electron scattering. As the stars evolve, the convective core retreats, and a zone of continuously varying composition is set up between the core and the envelope. Ten models have been obtained with core hydrogen content changing from 100 to 6 per cent. The evolutionary tracks of the models have been plotted in the H-R diagram. It is found that, although the individual tracks are very different from those found by other authors, the H-R diagram for stars of different masses but of the same age exhibits the well-known "knee," which occurs at the point of 11 per cent over-all reduction of hydrogen content.

I. INTRODUCTION

The course of stellar evolution is largely determined by the existence or nonexistence of general mixing currents in stellar interiors. If there are efficient mixing currents, a star



Alice crosses the mirror

neutrino energy losses

Plasma neutrinos

$$\gamma \rightarrow \nu_e \bar{\nu}_e$$

Photo neutrinos

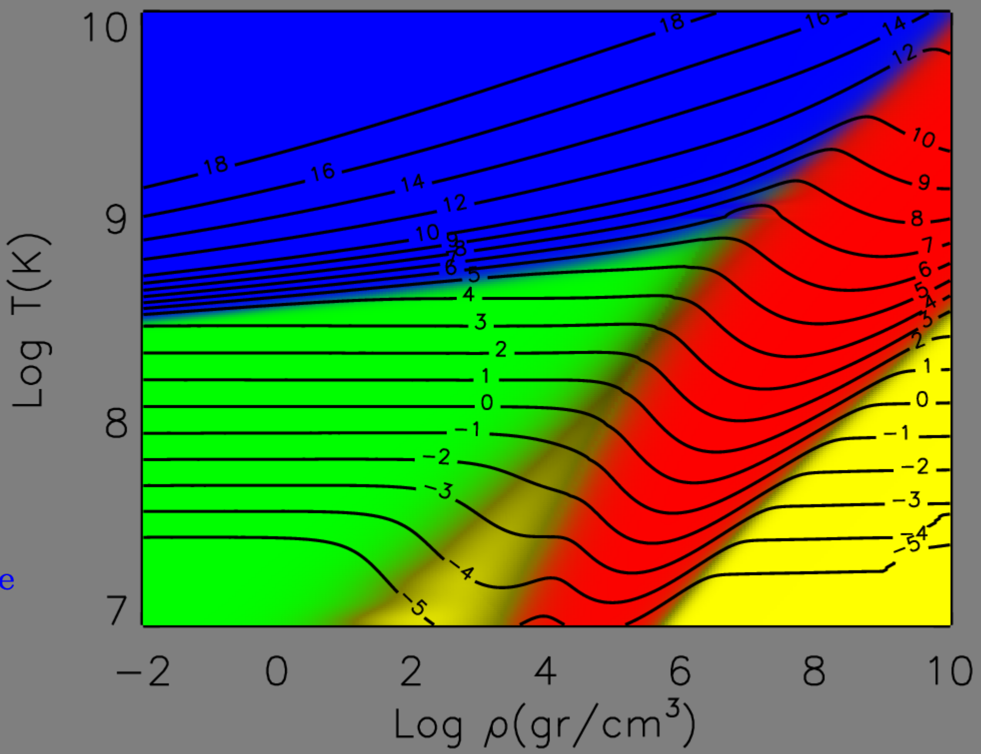
$$\gamma + e^- \rightarrow e^- \nu_e \bar{\nu}_e$$

Bremstrahlung

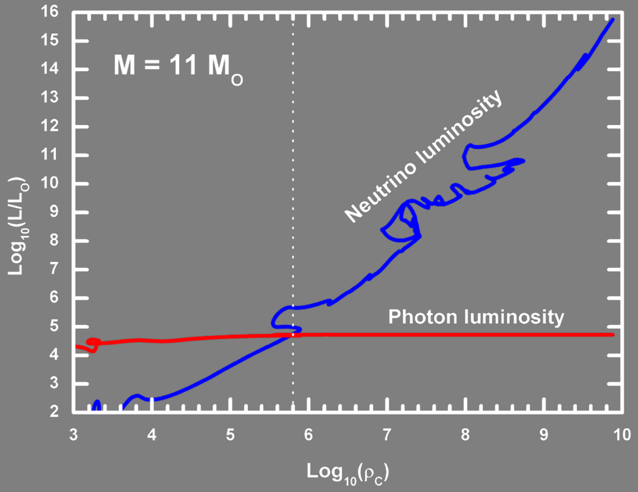
$$\gamma \; e^- \rightarrow \gamma \; e^- \; \nu_e \bar{\nu}_e$$

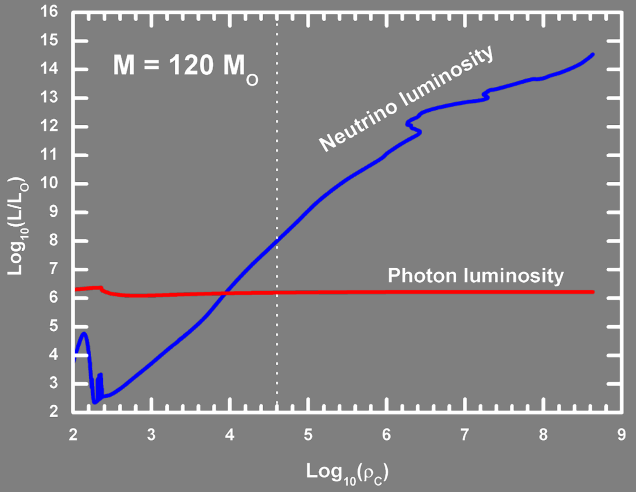
Pair neutrinos

$$\gamma\gamma \rightarrow e^+ e^- \rightarrow \nu_e \bar{\nu}_e$$



Pair neutrinos





Massive Stars: Carbon Burning

Following He burning the most abundant isotopes are ^{12}C,^{16}O

$T \simeq M^{2/3}\rho^{1/3}$ → $T \sim 8 \cdot 10^8$ K $\rho \sim 8 \cdot 10^5$ g/cm^3

$^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne} \longrightarrow {}^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$

$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

$^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$ →
- $^{23}\mathrm{Na}(p,\alpha)^{20}\mathrm{Ne}$
- $^{23}\mathrm{Na}(p,\gamma)^{24}\mathrm{Mg}$
- $^{23}\mathrm{Na}(\alpha,p)^{26}\mathrm{Mg}$

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$ →
- $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^+)^{25}\mathrm{Mg}$
- $^{24}\mathrm{Mg}(n,\gamma)^{25}\mathrm{Mg}$
- $^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

$^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}(\beta^+)^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$ →
- $^{27}\mathrm{Al}(n,\gamma)^{28}\mathrm{Al}(\beta^+)^{28}\mathrm{Si}$
- $^{27}\mathrm{Al}(p,\gamma)^{28}\mathrm{Si}$
- $^{27}\mathrm{Al}(p,\alpha)^{24}\mathrm{Mg}$

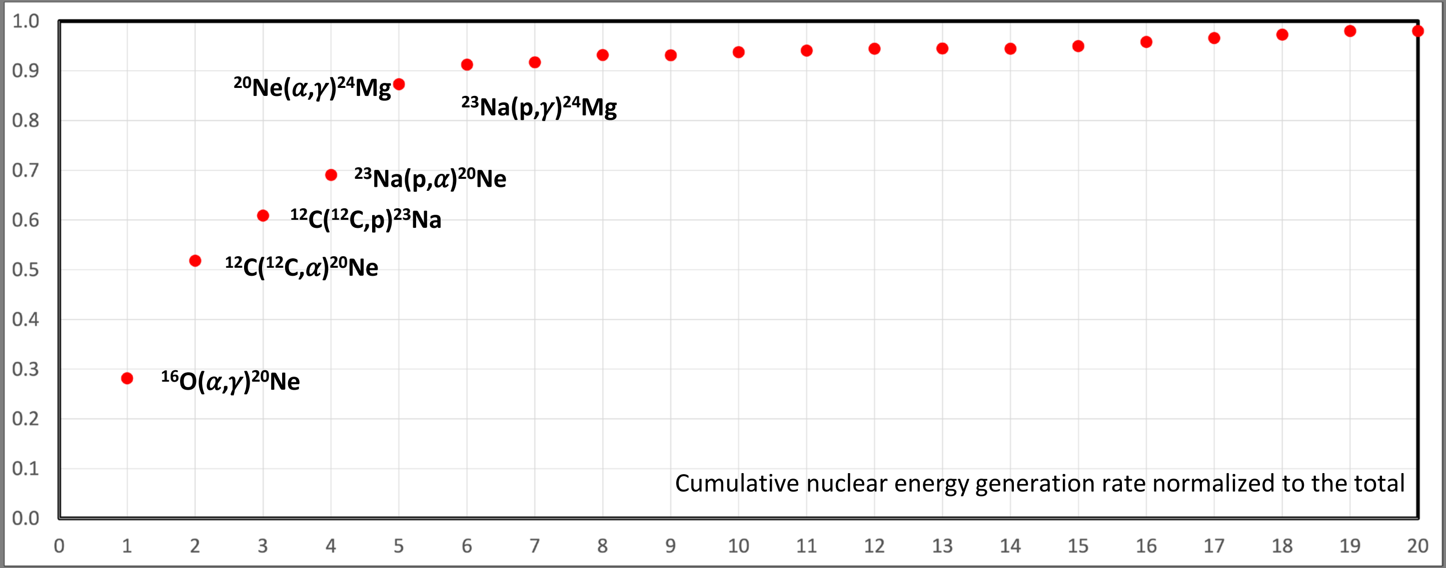
$^{22}\mathrm{Ne}(\alpha,n)$ → $s-$process

Main Products of C burning: ^{20}Ne, ^{23}Na, ^{24}Mg, ^{27}Al

Scondary Products of C burning: ^{25}Mg, ^{26}Mg, s-process

$2\ ^{12}\mathrm{C} \rightarrow\ ^{20}\mathrm{Ne} + \alpha$ → $E_{nuc} = 1.85\ 10^{17}$ erg/g

C burning



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
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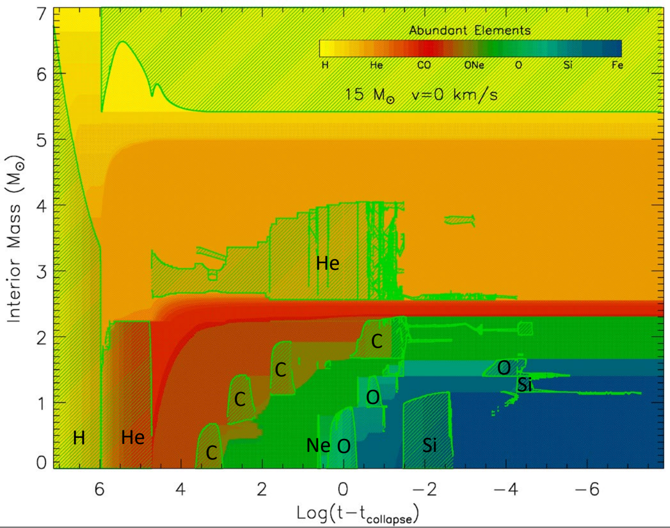
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
$^{20}Ne(\alpha,\gamma)^{24}Mg$
$^{23}Na(p,\gamma)^{24}Mg$
$^{23}Na(p,\alpha)^{20}Ne$
$^{12}C(^{12}C,p)^{23}Na$
$^{12}C(^{12}C,\alpha)^{20}Ne$
$^{16}O(\alpha,\gamma)^{20}Ne$
Cumulative nuclear energy generation rate normalized to the total

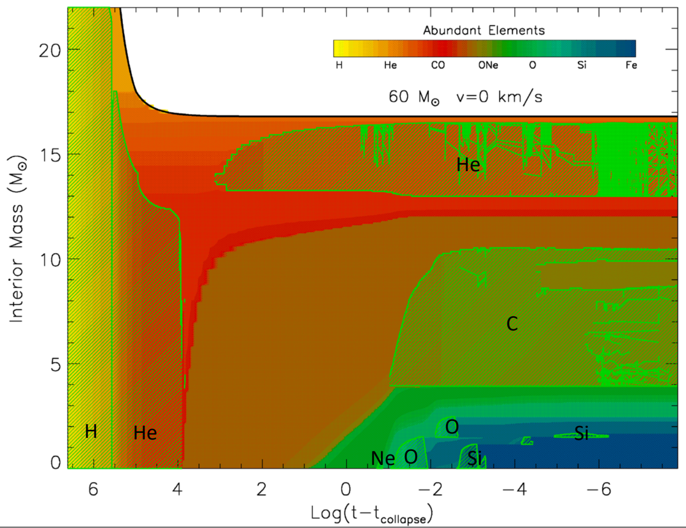

$^{12}C+^{12}C$
α
p

Massive Stars: Carbon Burning

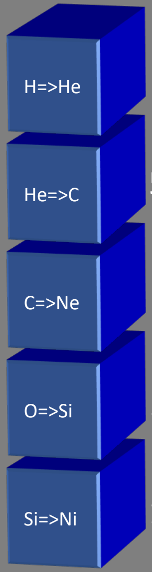
M < 25/30 $M_\odot$



M > 25/30 $M_\odot$



$M=80\ M_O\ \ t = E / L(10^6)$



$6.44\ 10^{18}$ erg gr^{-1}

$5.84\ 10^{17}$ erg gr^{-1}

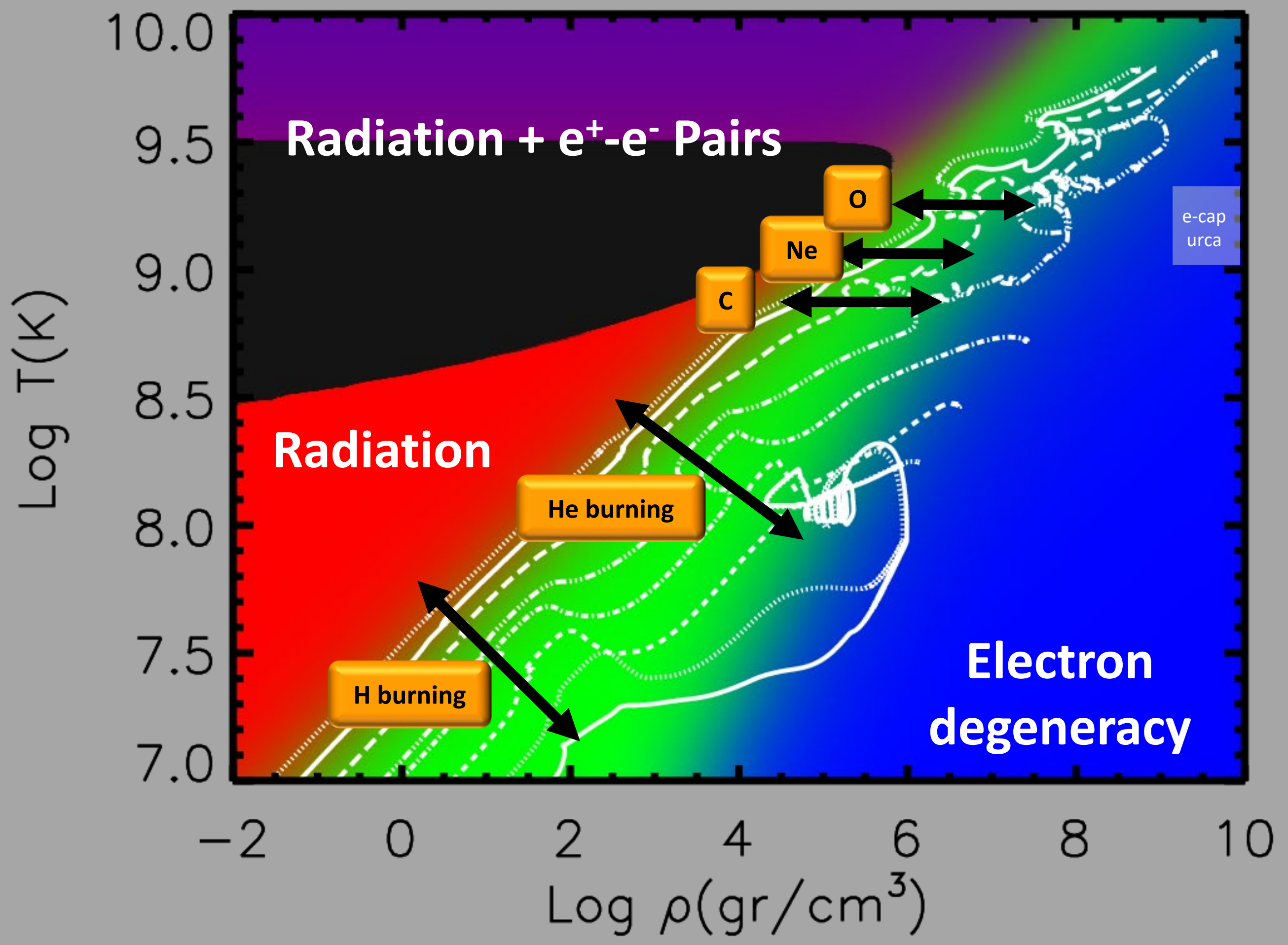
$1.85\ 10^{17}$ erg gr^{-1}

$2.89\ 10^{17}$ erg gr^{-1}

$1.88\ 10^{17}$ erg gr^{-1}

L => total luminosity: $L_\gamma + L_\nu$

Mcc	Estimated lifetime	Real lifetime	Revised lifetime	L_{TOT}
60	$6\ 10^6$	$3.2\ 10^6$		10^6
20	$2\ 10^5$	$3.3\ 10^5$		10^6
1.5	$4.5\ 10^3$	$4.7\ 10^2$	$4.5\ 10^2$	10^7
1	$4.8\ 10^3$	$4.6\ 10^{-2}$	$4.8\ 10^{-2}$	10^{11}
1	$3.1\ 10^3$	$4.3\ 10^{-3}$	$3.1\ 10^{-3}$	10^{12}



Radiation + e+-e- Pairs
Radiation
Electron degeneracy
e-cap urca
O
Ne
C
He burning
H burning
Log T(K)
Log ρ(gr/cm3)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10

Massive Stars: Neon Burning

Following C burning the most abundant isotopes are ^{16}O (He-burn.), ^{20}Ne, ^{23}Na, ^{24}Mg

$T \simeq M^{2/3}\rho^{1/3}$ → $T \sim 1.6 \cdot 10^9$ K $\quad \rho \sim 5 \cdot 10^6$ g/cm^3

$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$

$^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}$ →
- $^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$
- $^{24}\mathrm{Mg}(\alpha,p)^{27}\mathrm{Al}$ →
  - $^{27}\mathrm{Al}(\alpha,p)^{30}\mathrm{Si}$ →
    - $^{30}\mathrm{Si}(p,\gamma)^{31}\mathrm{P}(p,\alpha)^{28}\mathrm{Si}$
    - $^{30}\mathrm{Si}(n,\gamma)^{31}\mathrm{Si}(\beta^-)^{31}\mathrm{P}$
    - $^{30}\mathrm{Si}(\alpha,\gamma)^{34}\mathrm{S}$
  - $^{27}\mathrm{Al}(p,\gamma)^{28}\mathrm{Si}$
  - $^{27}\mathrm{Al}(n,\gamma)^{28}\mathrm{Al}(\beta^-)^{28}\mathrm{Si}$
  - $^{27}\mathrm{Al}(\alpha,\gamma)^{31}\mathrm{P}$
- $^{24}\mathrm{Mg}(n,\gamma)^{25}\mathrm{Mg}$ →
  - $^{25}\mathrm{Mg}(\alpha,n)^{28}\mathrm{Si}(n,\gamma)^{29}\mathrm{Si}$
  - $^{25}\mathrm{Mg}(n,\gamma)^{26}\mathrm{Al}(\beta^+)^{26}\mathrm{Mg}$
  - $^{25}\mathrm{Mg}(n,\gamma)^{26}\mathrm{Mg}$
  - $^{25}\mathrm{Mg}(\alpha,p)^{28}\mathrm{Al}(\beta^-)^{28}\mathrm{Si}$

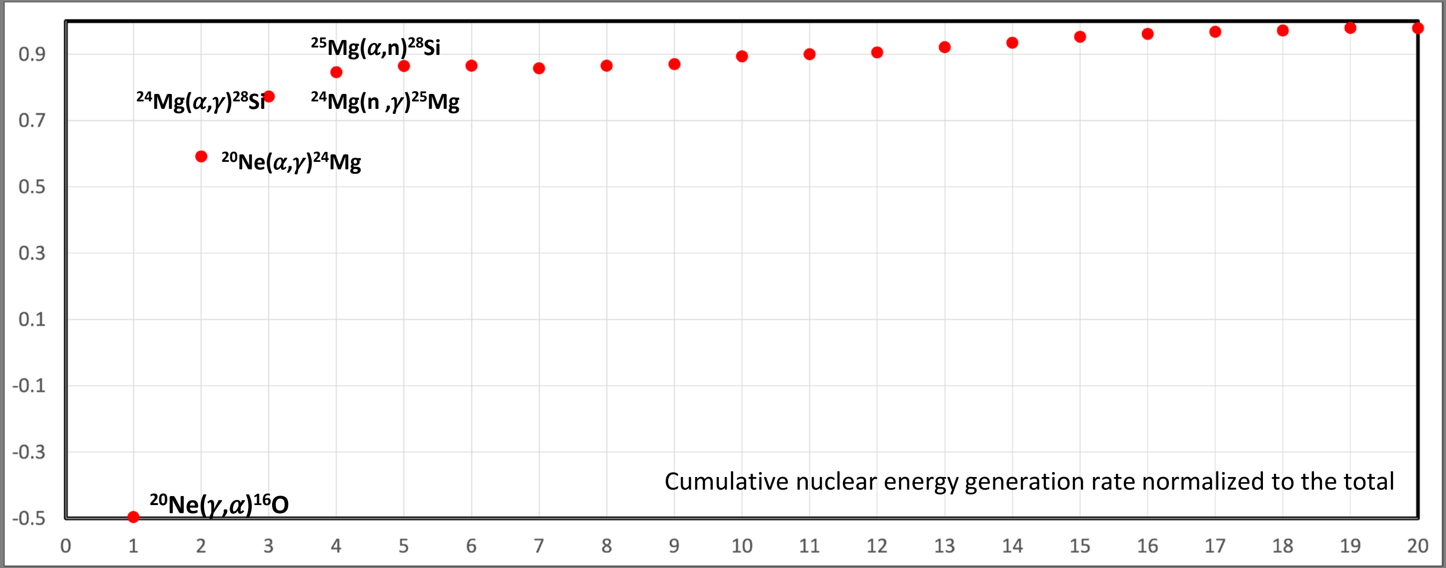
$^{23}\mathrm{Na}(\alpha,p)^{26}\mathrm{Mg}$ →
- $^{26}\mathrm{Mg}(\alpha,n)^{29}\mathrm{Si}$
- $^{26}\mathrm{Mg}(p,\gamma)^{27}\mathrm{Al}$

Main Products: ^{16}O, ^{24}Mg , ^{28}Si

Secondary Products: ^{25,26}Mg, ^{27}Al, ^{29,30}Si, ^{31}P

2 ^{20}Ne → ^{16}O+ ^{24}Mg → E_{nuc} = 1.10 10^{17} erg/g

Ne burning



0.9
0.7
0.5
0.3
0.1
-0.1
-0.3
-0.5
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17
18
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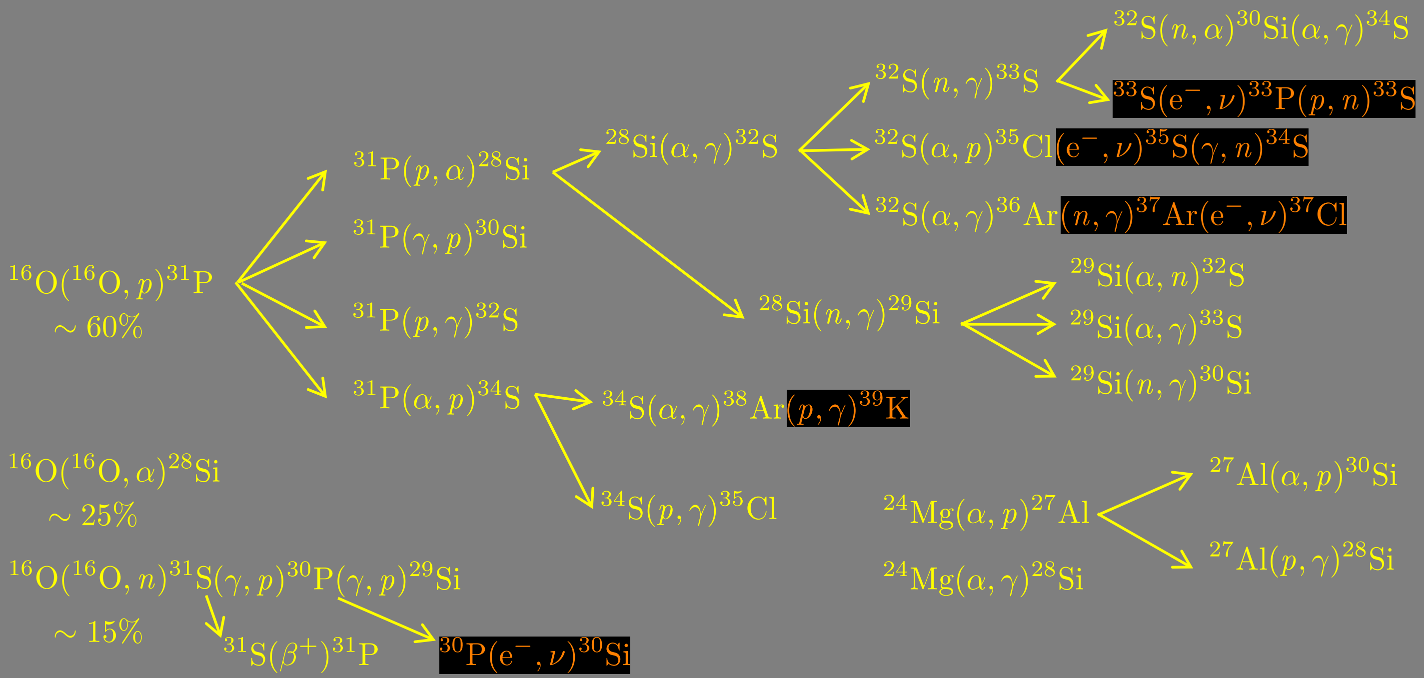
20
$^{25}Mg(\alpha,n)^{28}Si$
$^{24}Mg(\alpha,\gamma)^{28}Si$
$^{24}Mg(n,\gamma)^{25}Mg$
$^{20}Ne(\alpha,\gamma)^{24}Mg$
$^{20}Ne(\gamma,\alpha)^{16}O$
Cumulative nuclear energy generation rate normalized to the total

Massive Stars: Oxygen Burning

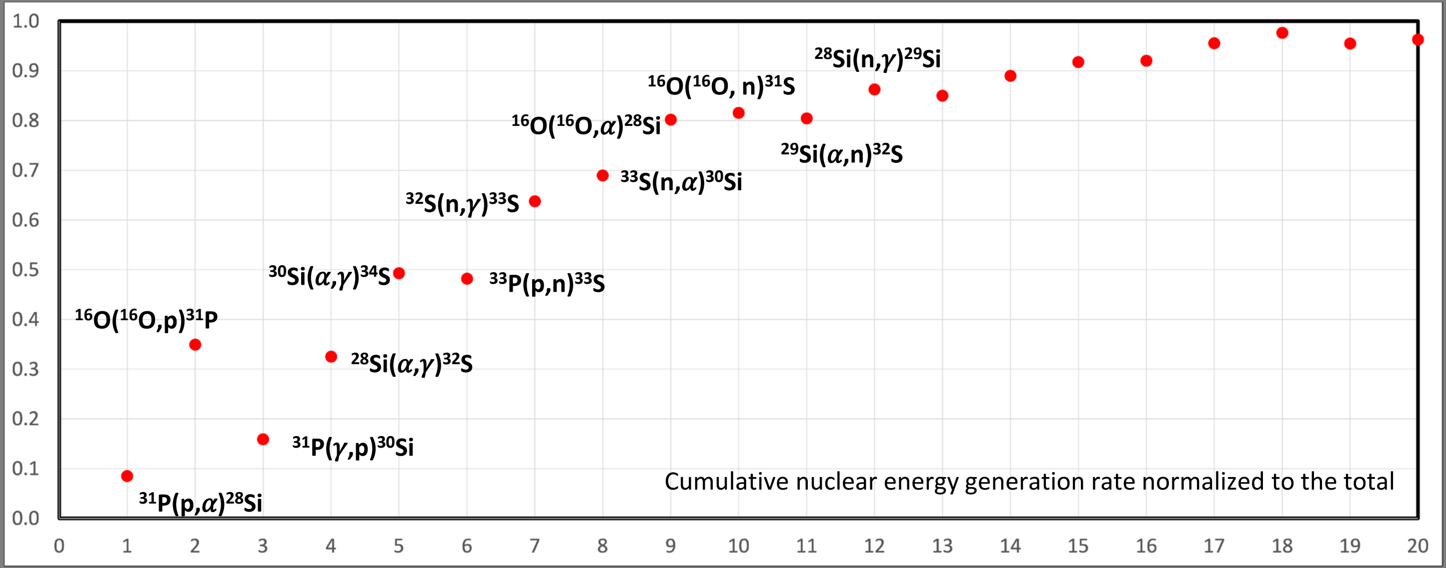
The most abundant nuclei left by the Ne burning are: ^{16}O, ^{24}Mg, ^{28}Si



Main Products: ^{28,30}Si, ^{32,34}S, ^{38}Ar

Scondary Products: ^{35,37}Cl, ^{36}Ar, ^{39}K

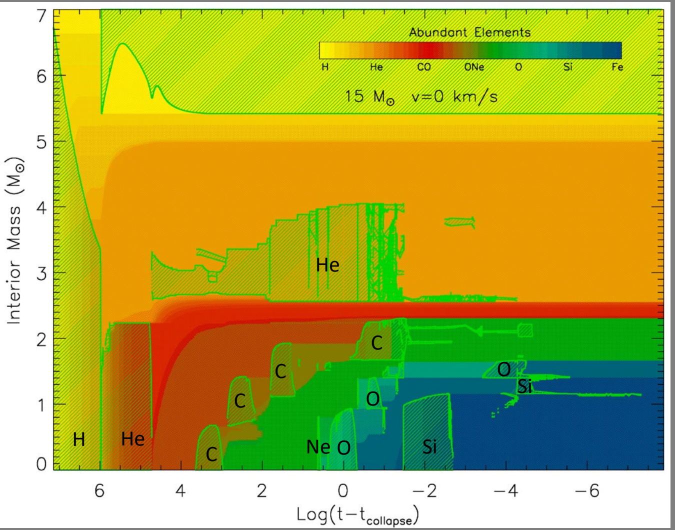
O burning



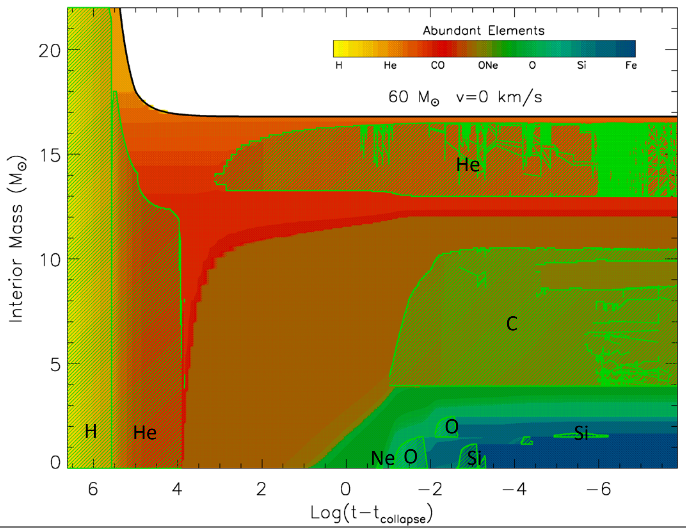
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
$^{31}P(p,\alpha)^{28}Si$
$^{16}O(^{16}O,p)^{31}P$
$^{31}P(\gamma,p)^{30}Si$
$^{28}Si(\alpha,\gamma)^{32}S$
$^{30}Si(\alpha,\gamma)^{34}S$
$^{33}P(p,n)^{33}S$
$^{32}S(n,\gamma)^{33}S$
$^{33}S(n,\alpha)^{30}Si$
$^{16}O(^{16}O,\alpha)^{28}Si$
$^{16}O(^{16}O, n)^{31}S$
$^{29}Si(\alpha,n)^{32}S$
$^{28}Si(n,\gamma)^{29}Si$
Cumulative nuclear energy generation rate normalized to the total

Massive Stars: Carbon Burning

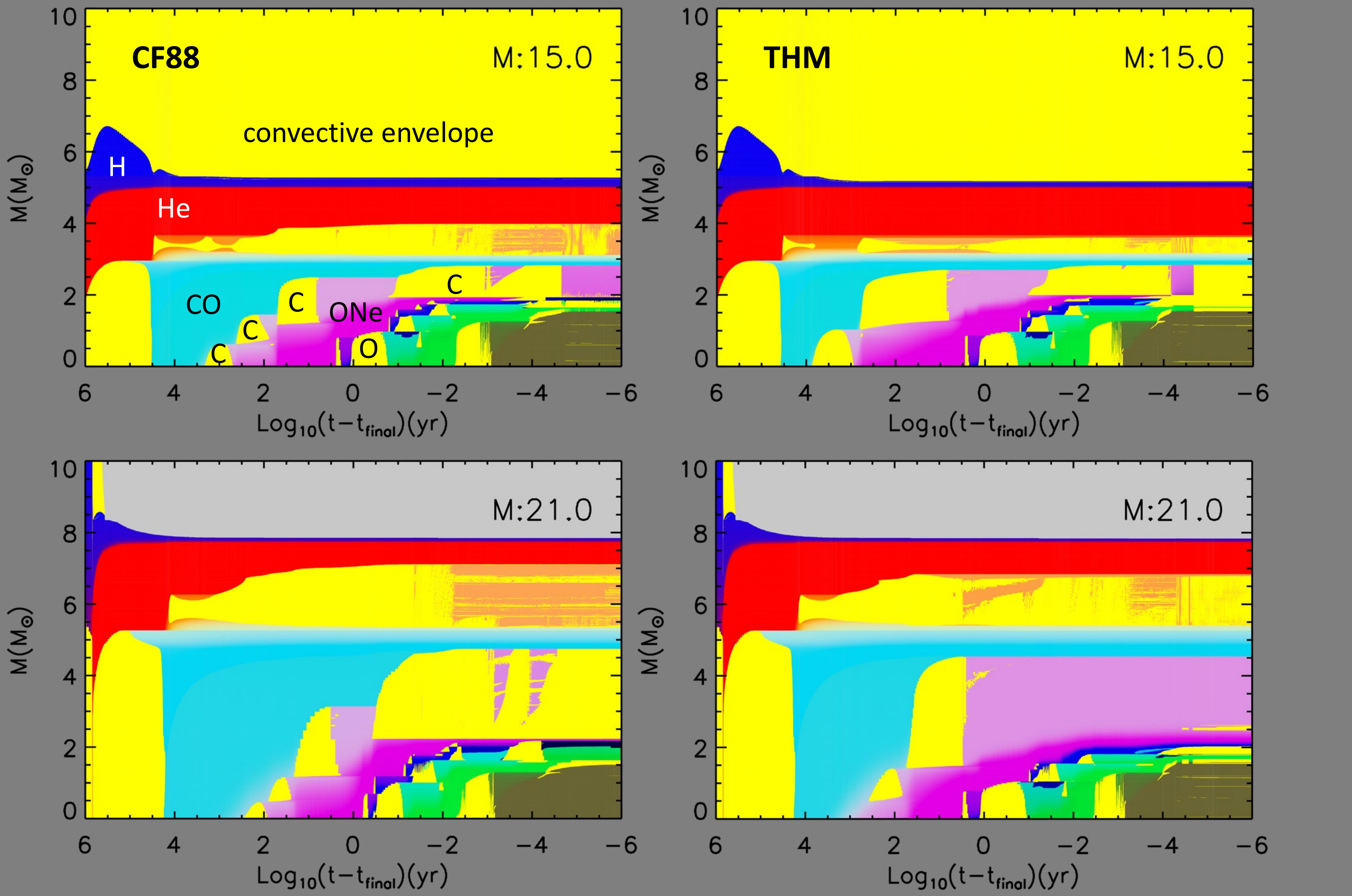
$M < 25/30\ M_\odot$



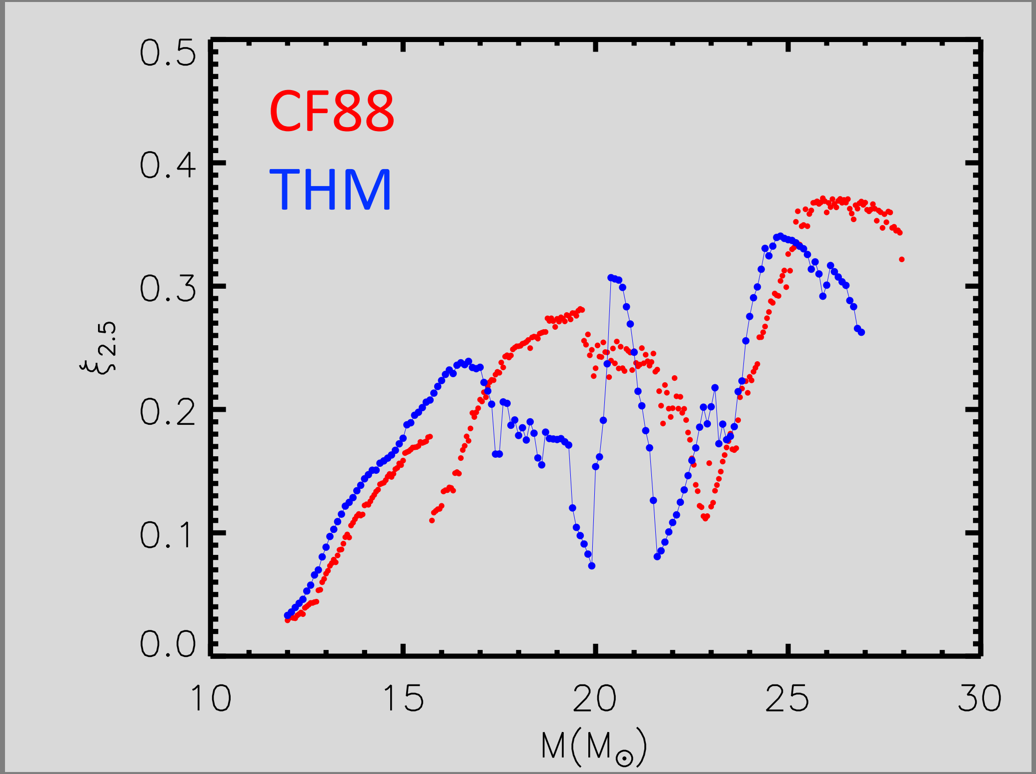
$M > 25/30\ M_\odot$



The advanced burning



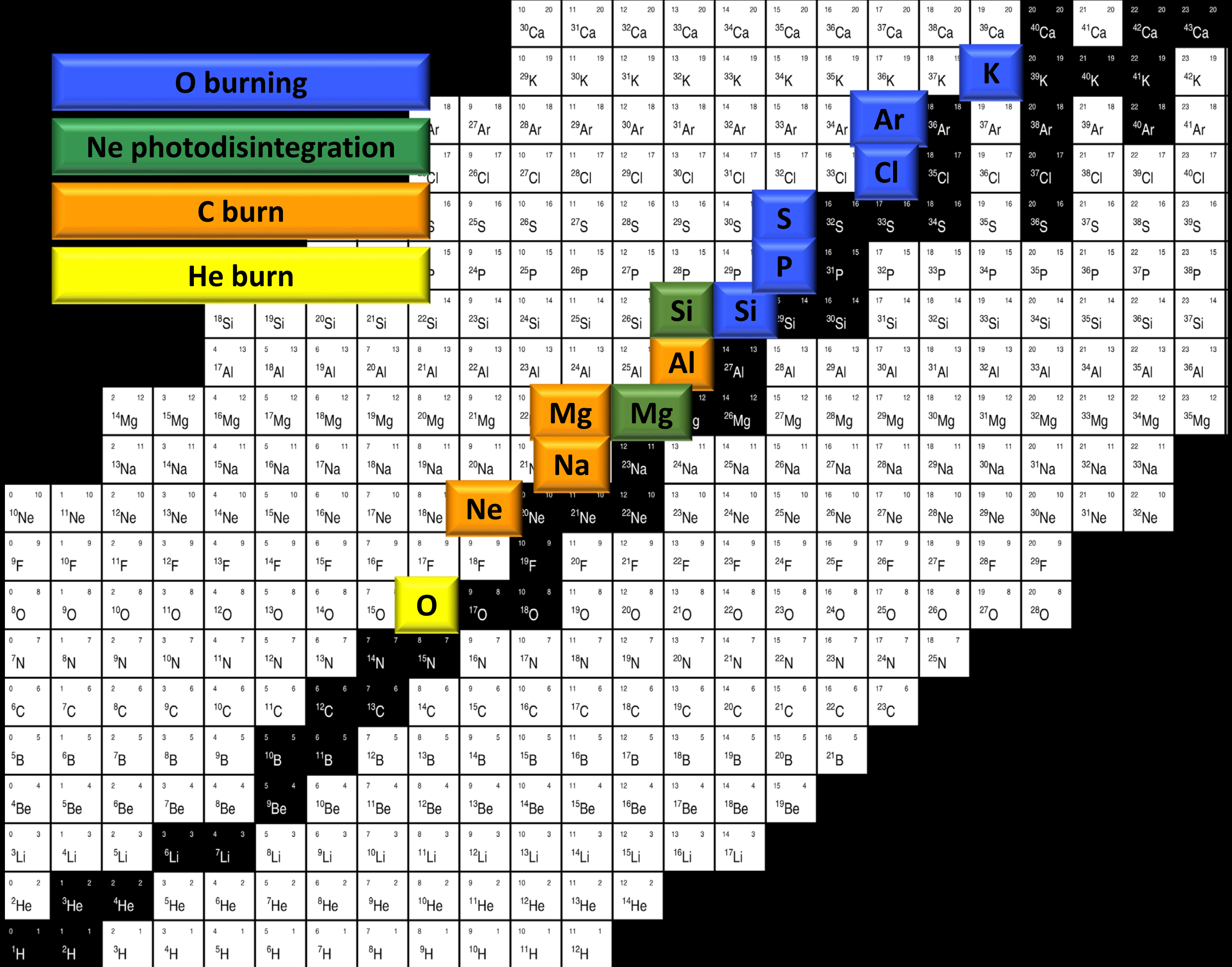
The final compactness

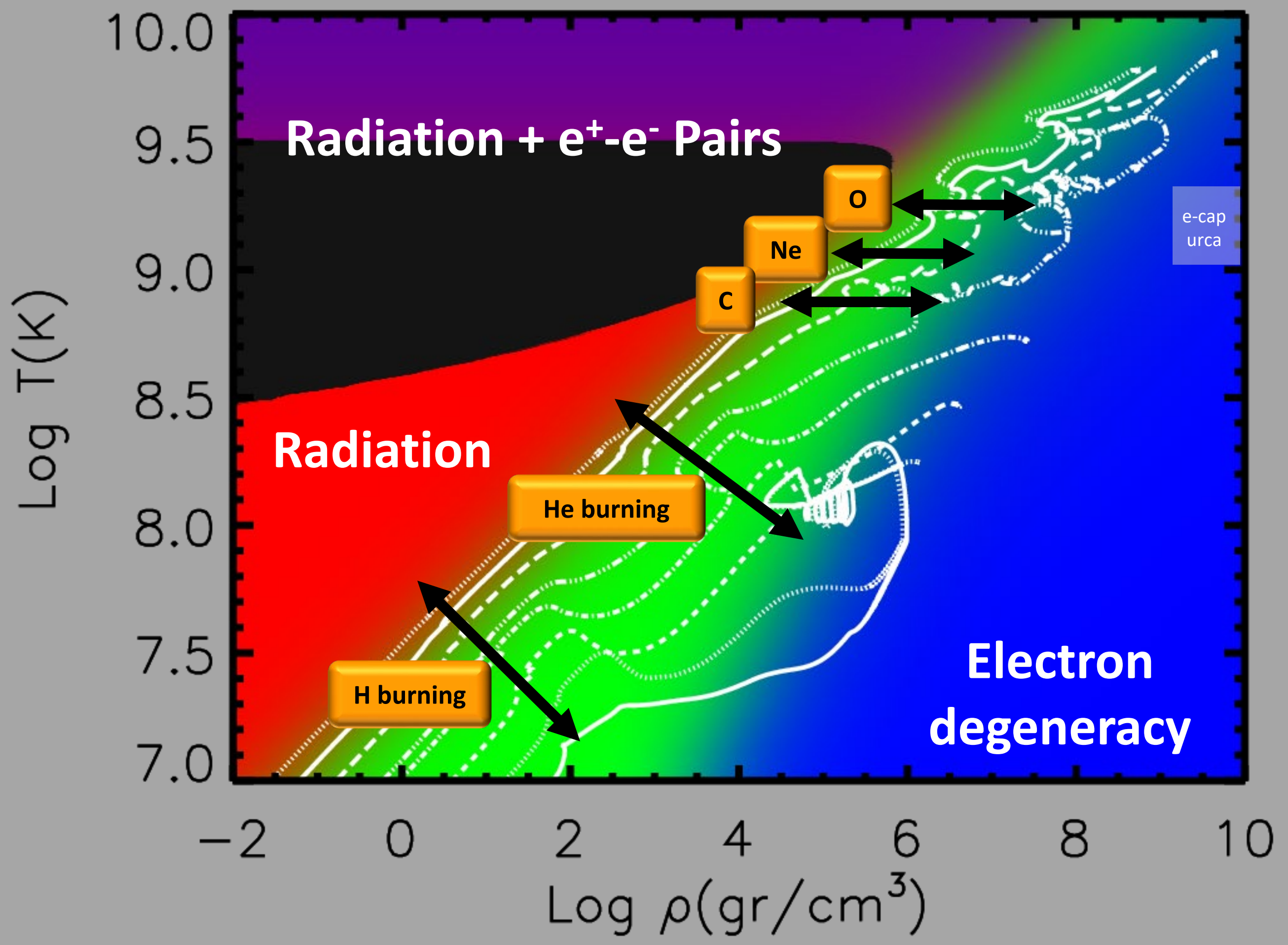


Compactness parameter ξ

(O' Connor & Ott 2011, ApJ 730,70)

$$\xi_i = \frac{M_i(M_\odot)}{R_i(10^3\ km)}$$


O burning
Ne photodisintegration
C burn
He burn
K
Ar
Cl
S
P
Si
Si
Al
Mg
Mg
Na
Ne
O



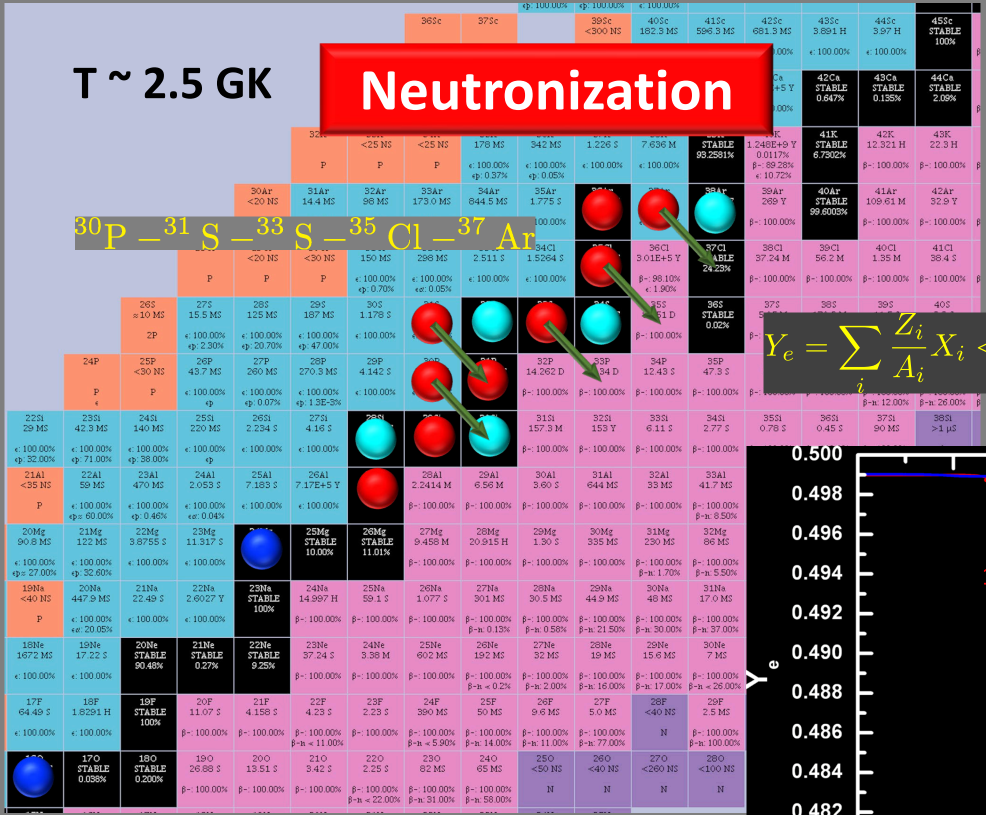
Radiation + e+-e- Pairs
Radiation
Electron degeneracy
O
Ne
C
He burning
H burning
e-cap
urca
Log T(K)
Log ρ(gr/cm3)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
−2
0
2
4
6
8
10

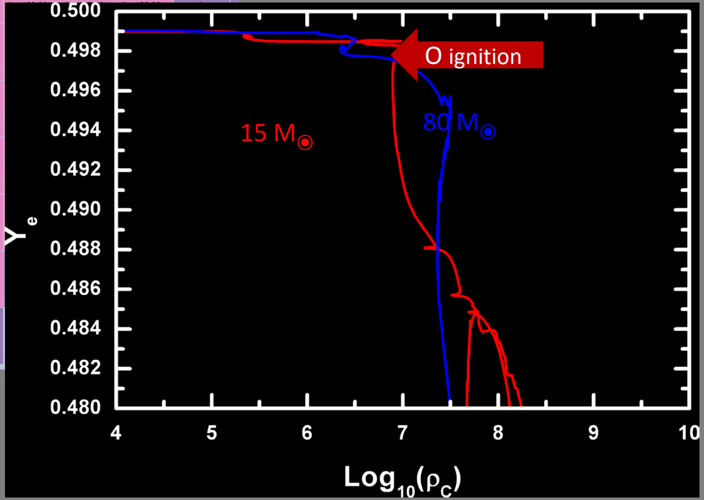
Neutronization

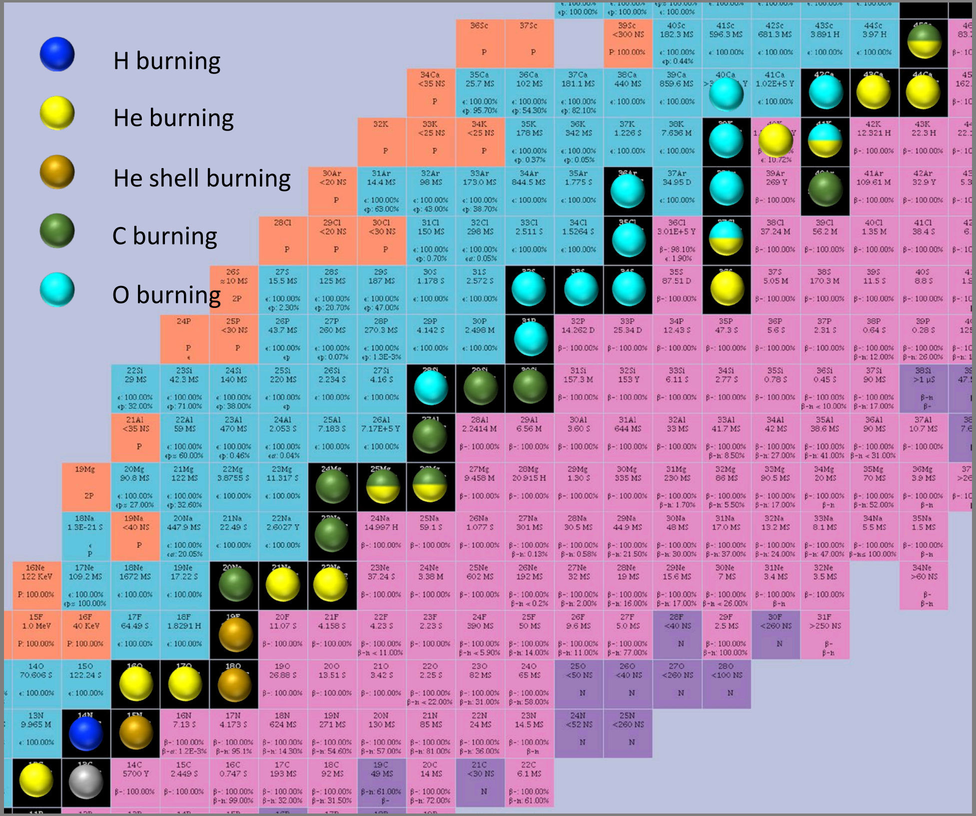
T ~ 2.5 GK

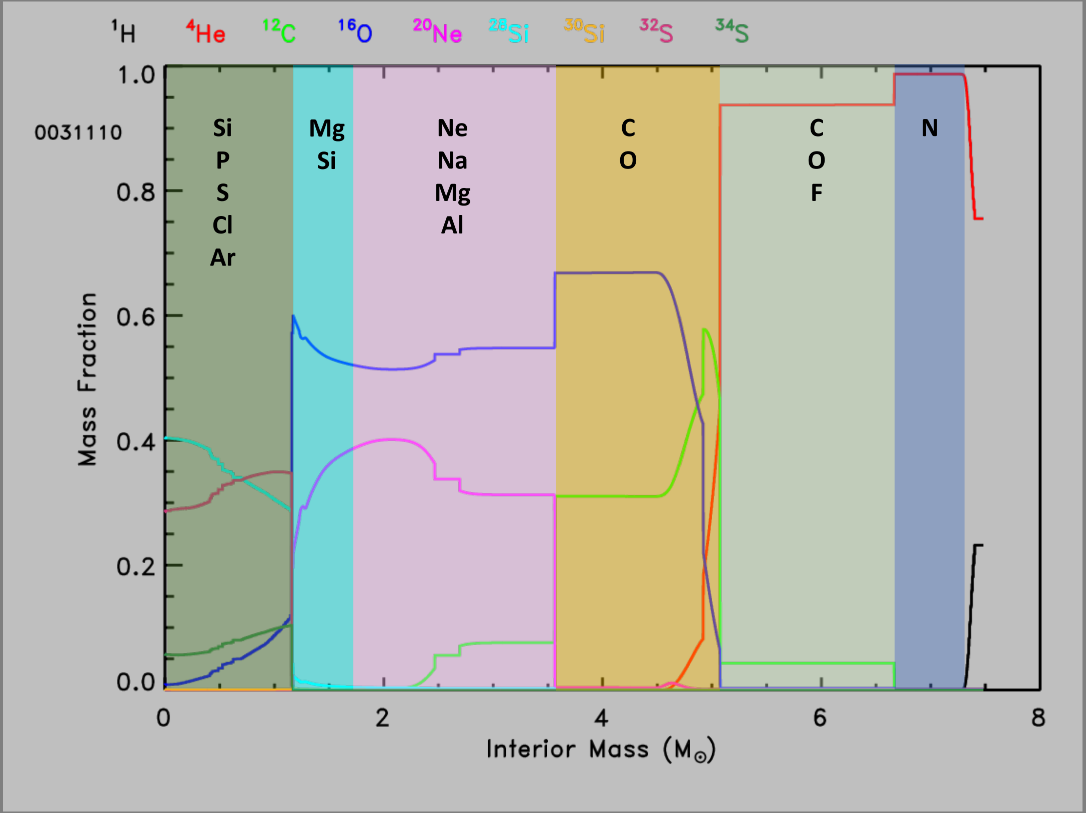
$^{30}P - ^{31}S - ^{33}S - ^{35}Cl - ^{37}Ar$

$$Y_e = \sum_i \frac{Z_i}{A_i} X_i < 0.5$$






H burning
He burning
He shell burning
C burning
O burning



1H
4He
12C
16O
20Ne
28Si
30Si
32S
34S
0031110
Si
P
S
Cl
Ar
Mg
Si
Ne
Na
Mg
Al
C
O
C
O
F
N
1.0
0.8
0.6
0.4
0.2
0.0
Mass Fraction
0
2
4
6
8
Interior Mass (M⊙)

Beyond the O burning matter approaches progressively the Nuclear Statistical Equilibrium

At the central O exhaustion => $T \sim 2.5 \cdot 10^9$ K

direct	**reverse**
$i + k \rightarrow j + l$	$j + l \rightarrow i + k$

$$< \sigma v >_{jl} \;\propto\; < \sigma v >_{ik} \; e^{-\frac{Q_{ik}[MeV]}{0.086 \; T_9}}$$

$$R_{ik} \sim R_{jl}$$

To quantify how close a pair of processes is to the equilibrium let us define a parameter φ:

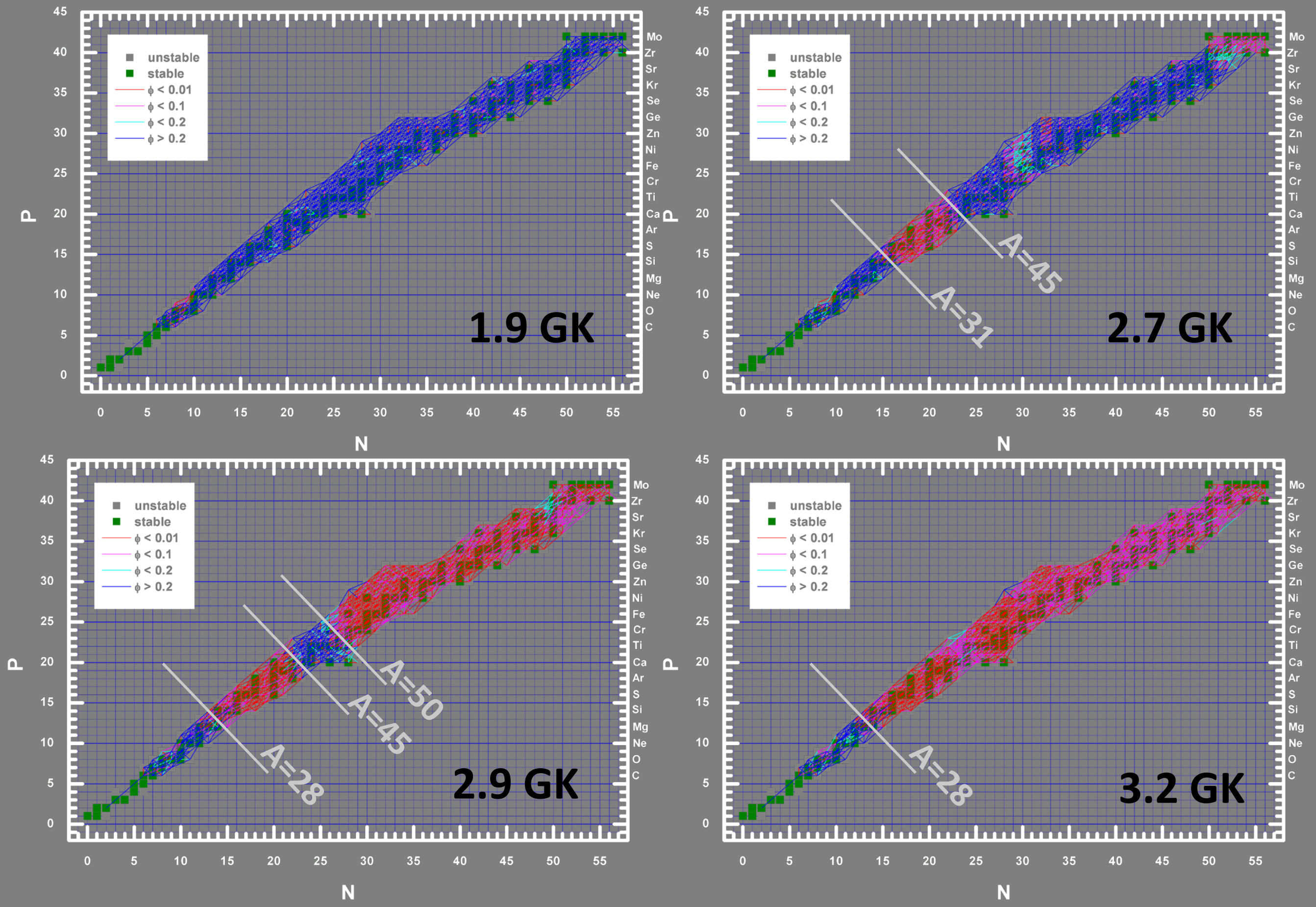
$$\varphi(i,j) = \frac{|r_{ij} - r_{ji}|}{\max(r_{ij}, r_{ji})}$$

obviously

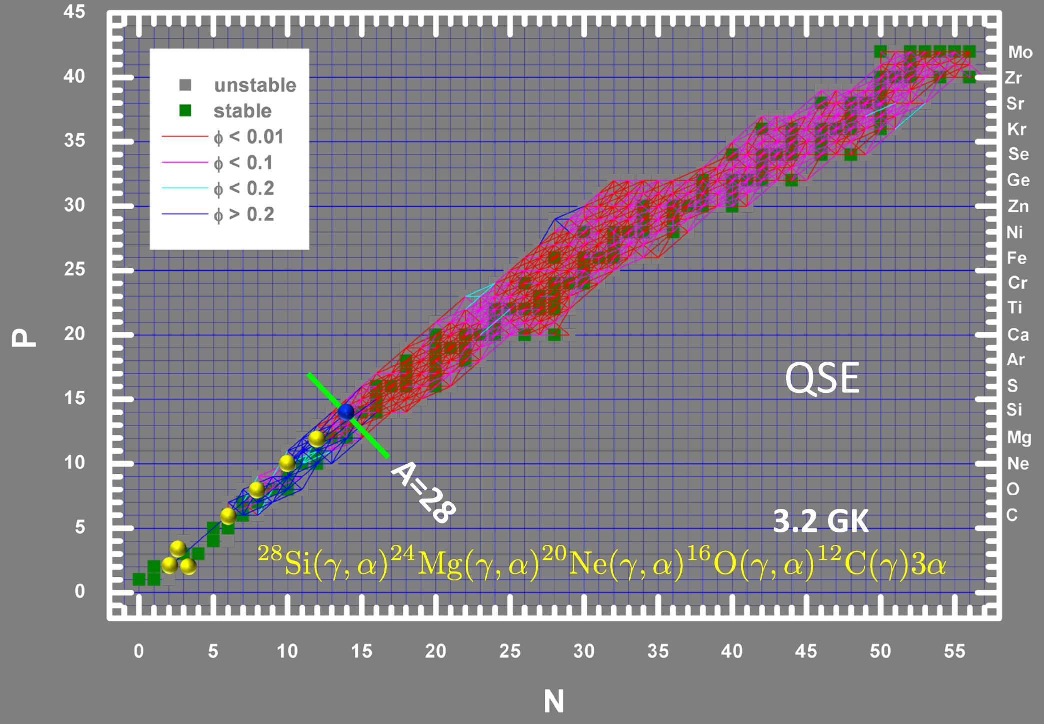
$\varphi \rightarrow 0$ full equilibrium

$\varphi \rightarrow 1$ no equilibrium

Beyond O burning…the path towards the Nuclear Startistical Equilibrium



…the approach to the Nuclear Statistical Equilibrium



Nuclear Statistical Equilibrium

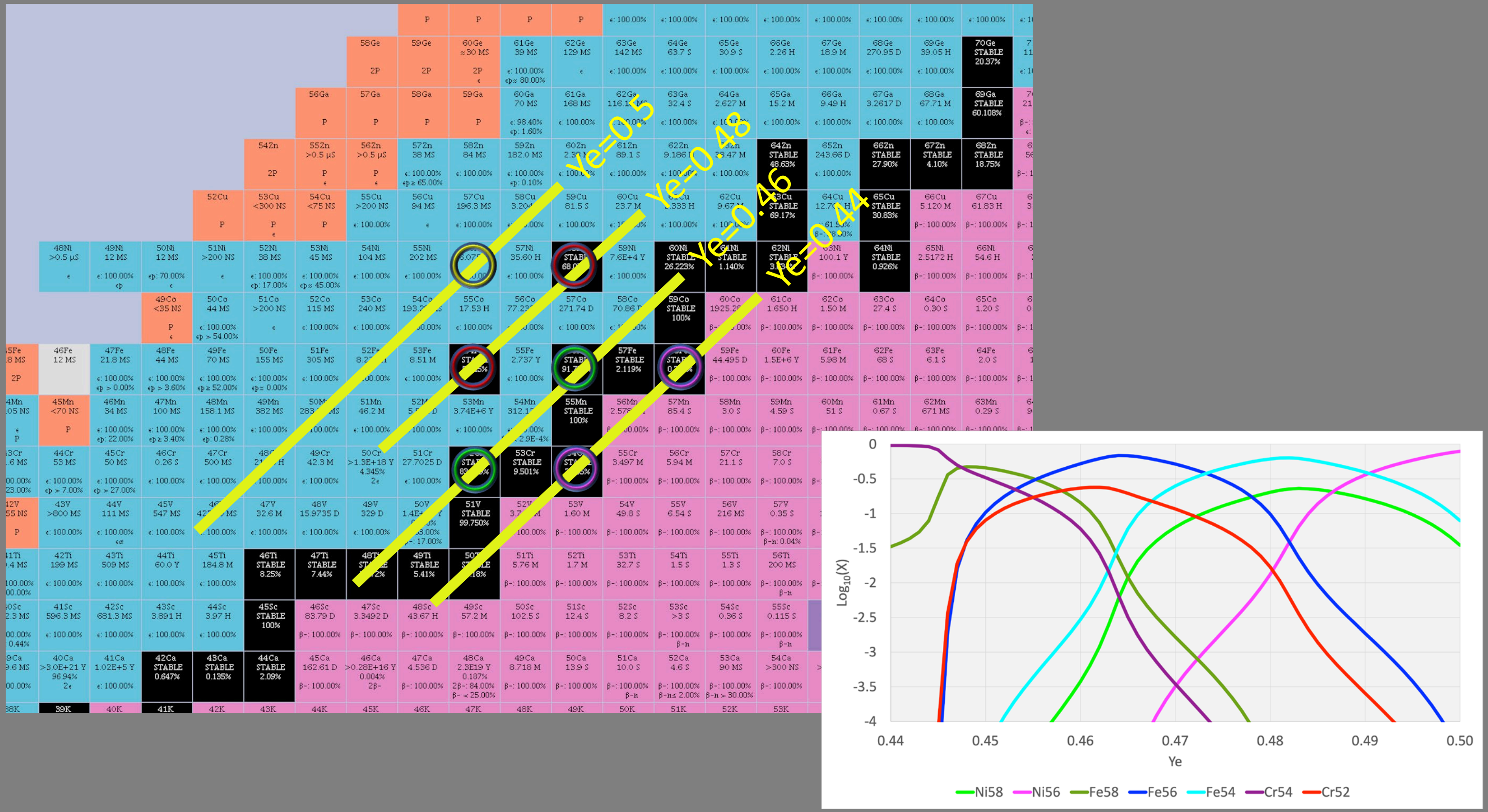
At T>5 GK full equilibrium between direct and reverse processes

$$(N, Z) \rightleftarrows Zp + Nn$$

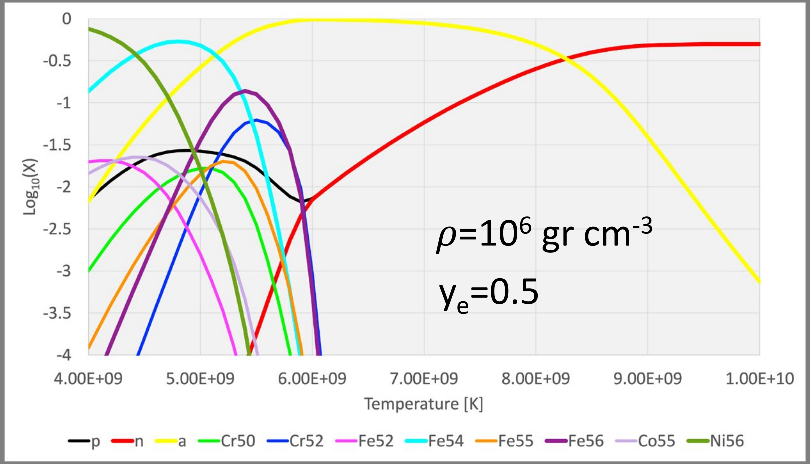
$$\mathrm{y_{i(Z,N)}} = \omega(\mathrm{z, n})\,(\rho \mathrm{N_A})^{\mathrm{A}-1} \left(\frac{\mathrm{A m_p k T}}{2\pi\hbar^2}\right)^{3/2} \mathrm{y_p^z y_n^n} 2^{-\mathrm{A}} \left(\frac{2\pi\hbar^2}{\mathrm{m_p k T}}\right)^{\mathrm{A}\frac{3}{2}} \mathrm{e}^{-\frac{\mathrm{Q(z,n)}}{\mathrm{kT}}}$$

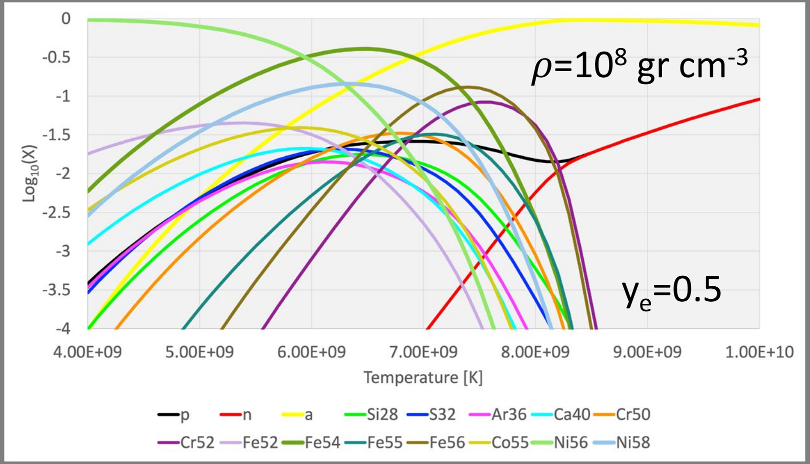
$$\mathrm{y_{i(Z,N)}} = f(\mathrm{A, T}, \rho)\mathrm{y_p^z y_n^n e}^{-\frac{\mathrm{Q(z,n)}}{\mathrm{kT}}}$$

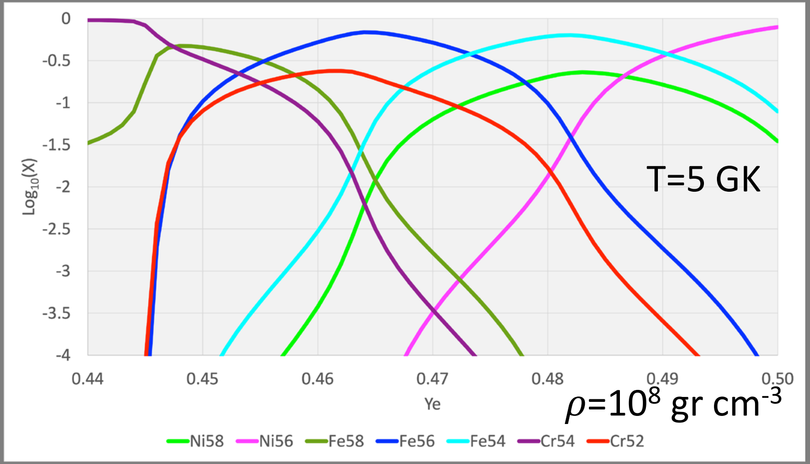
Nuclear Statistical Equilibrium

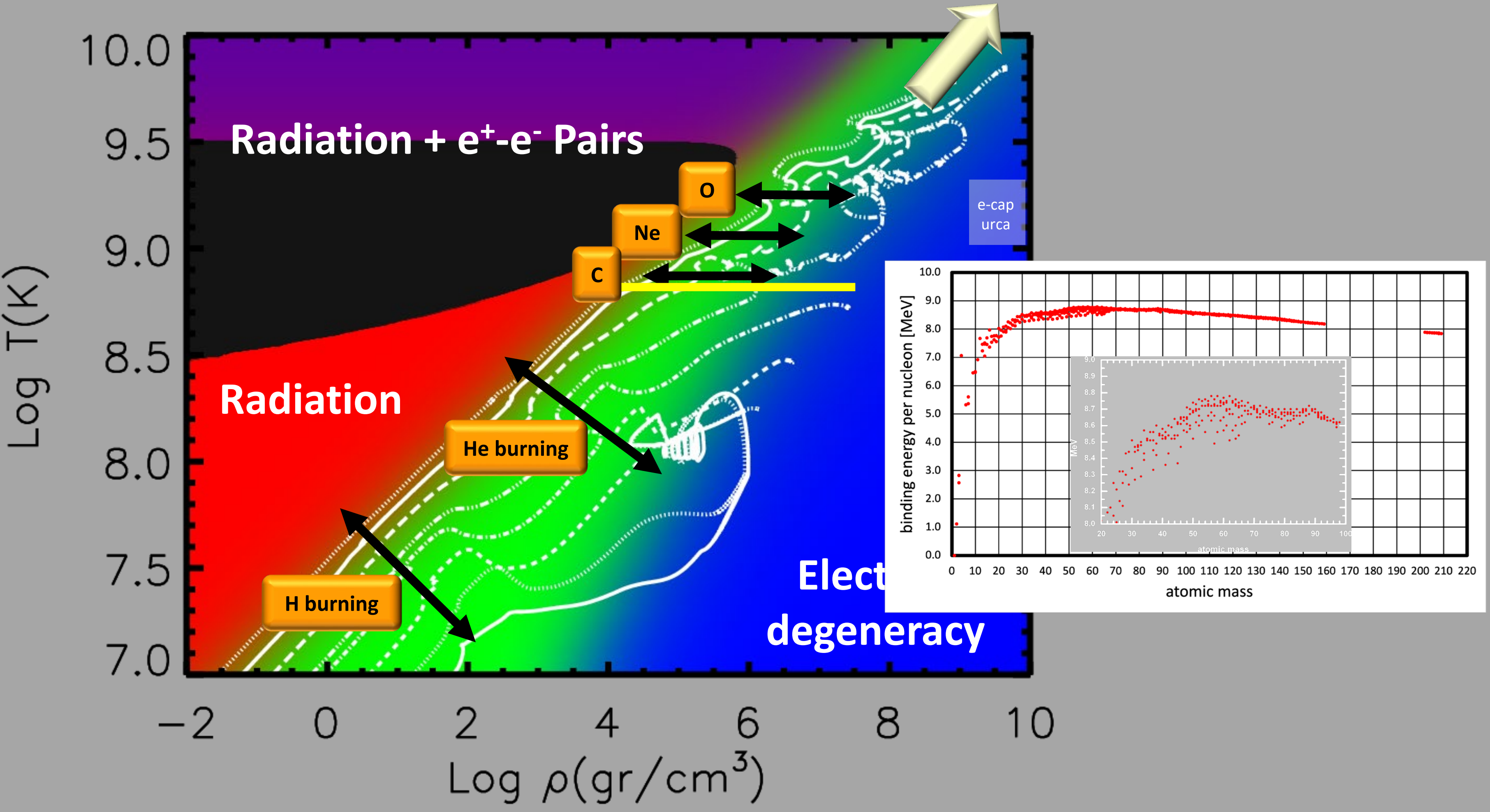


Nuclear Statistical Equilibrium



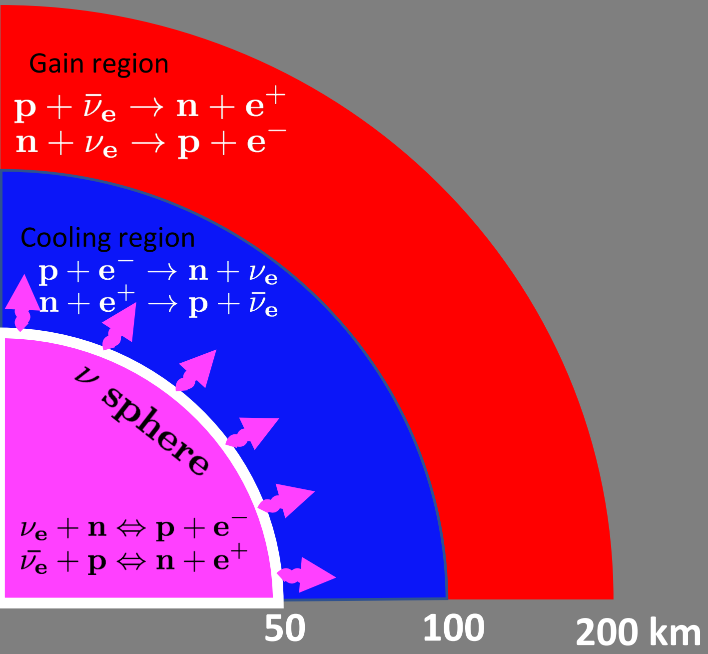


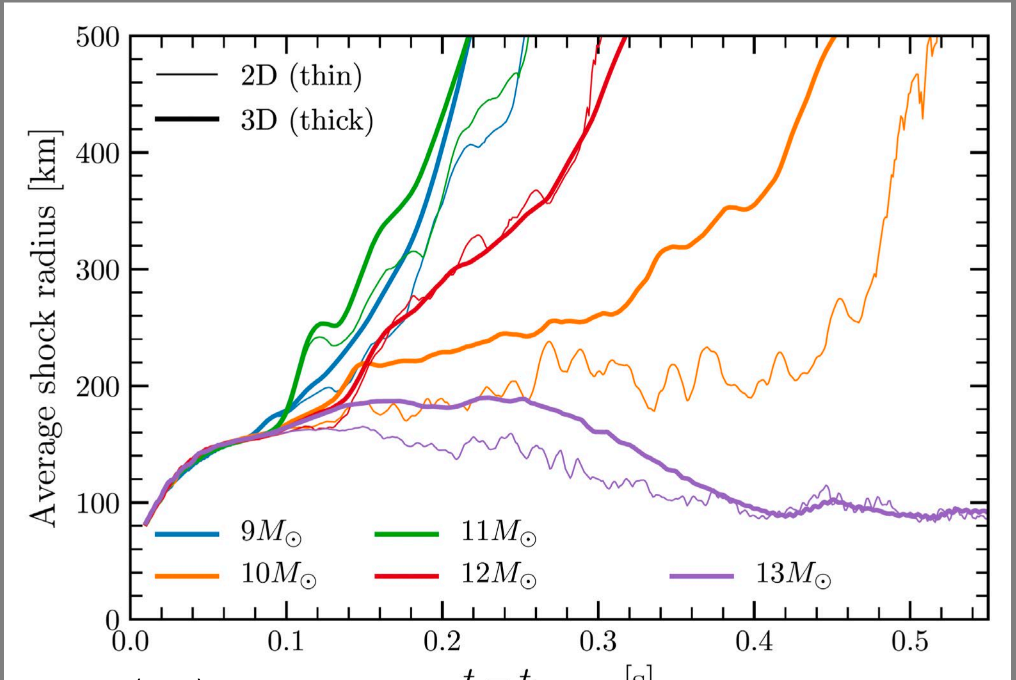




Radiation + e⁺-e⁻ Pairs
Radiation
O
Ne
C
He burning
H burning
e-cap
urca
Elect
degeneracy
Log T(K)
Log ρ(gr/cm³)
binding energy per nucleon [MeV]
atomic mass

Total amount of energy released by the gravitational collapse amounts to, roughly: $\mathbf{E = 1.6\ 10^{53}\ erg}$





Burrows+ (2019) MNRAS 485, 3168

Total amount of energy released by the gravitational collapse amounts to, roughly:

$$\mathbf{E = 1.6\ 10^{53}\ erg}$$

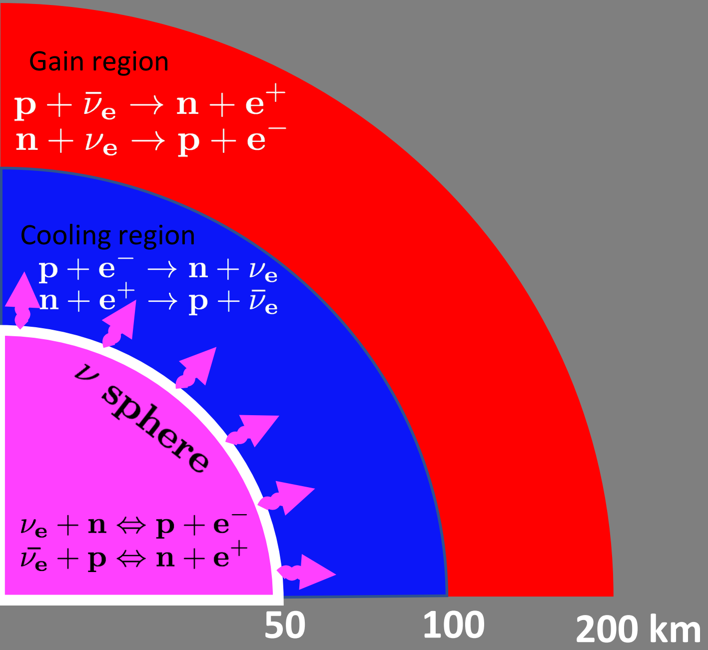


Table 2. For the runs presented in this paper, the mean shock radius (in units of 1000 kilometres) and mean shock speed (in units of 1000 km s^{-1}) at the end of each simulation. Note that the shock is still stalled at the end of the simulation only for the 2D and 3D 13-$M_\odot$ models.

	t (final) (s)	Mean shock radius (1000 km)	Mean shock speed (1000 km s^{-1})
s9.0-2D	1.41	15.24	14.19
s9.0-3D	1.042	12.42	16.29
s10.0-2D	1.41	7.70	10.62
s10.0-3D	0.767	1.96	6.65
s11.0-2D	1.41	9.18	7.41
s11.0-3D	0.568	2.75	8.00
s12.0-2D	1.41	8.72	8.08
s12.0-3D	0.694	2.66	6.85
s13.0-2D	1.311	0.06	0.067
s13.0-3D	0.674	0.09	0.048

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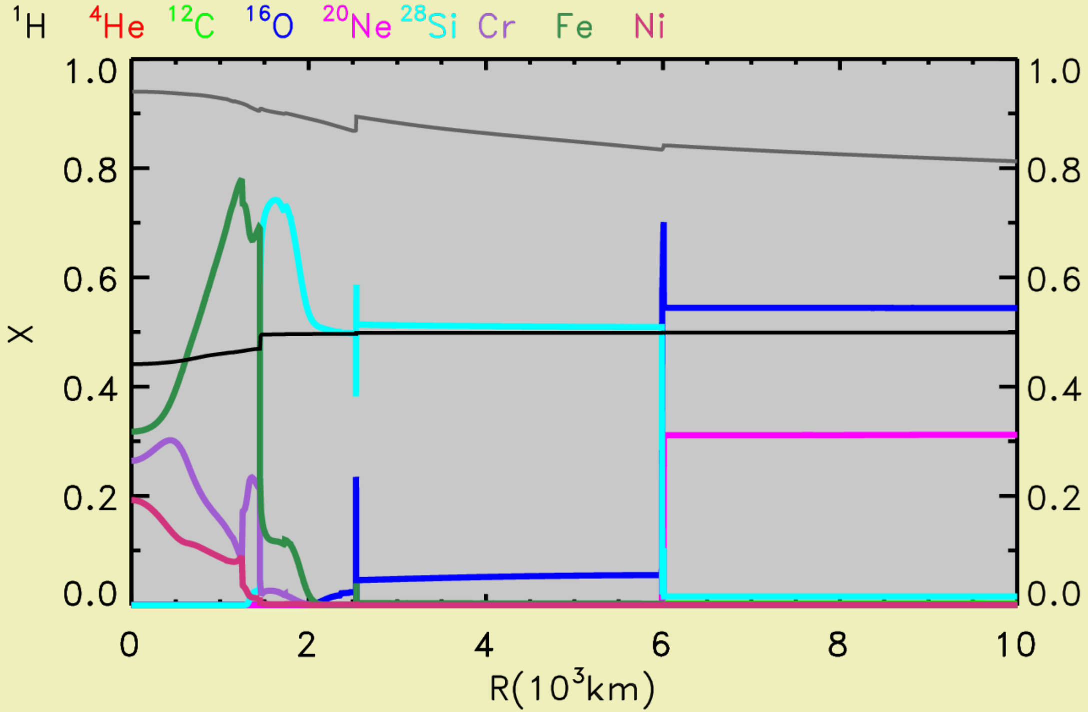
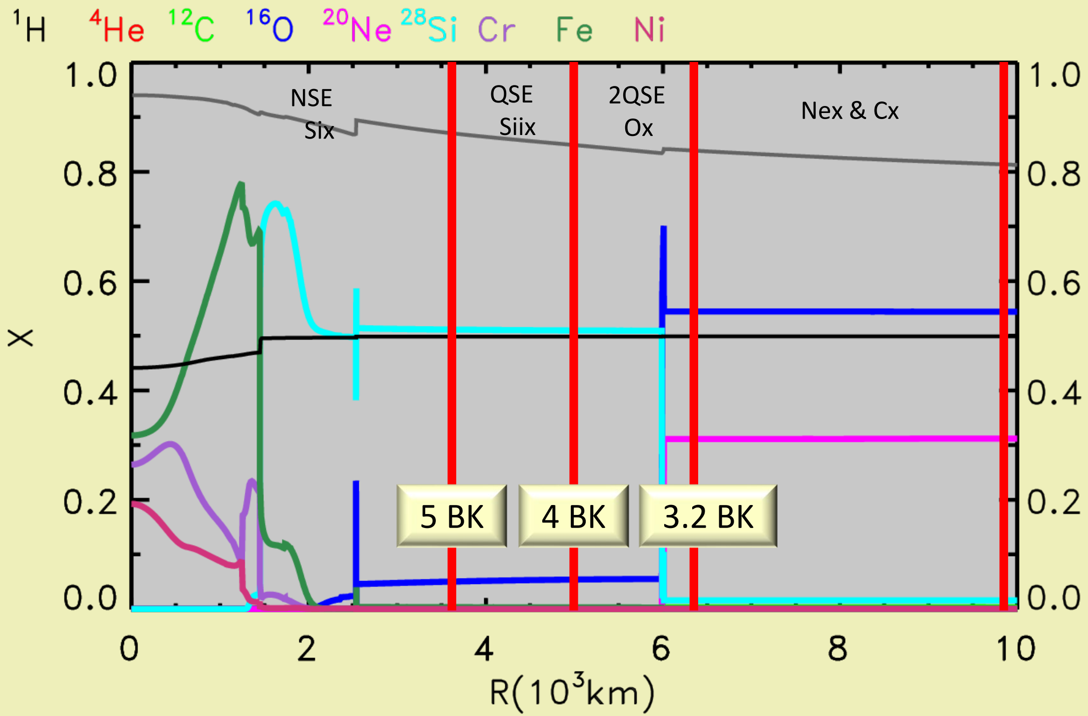
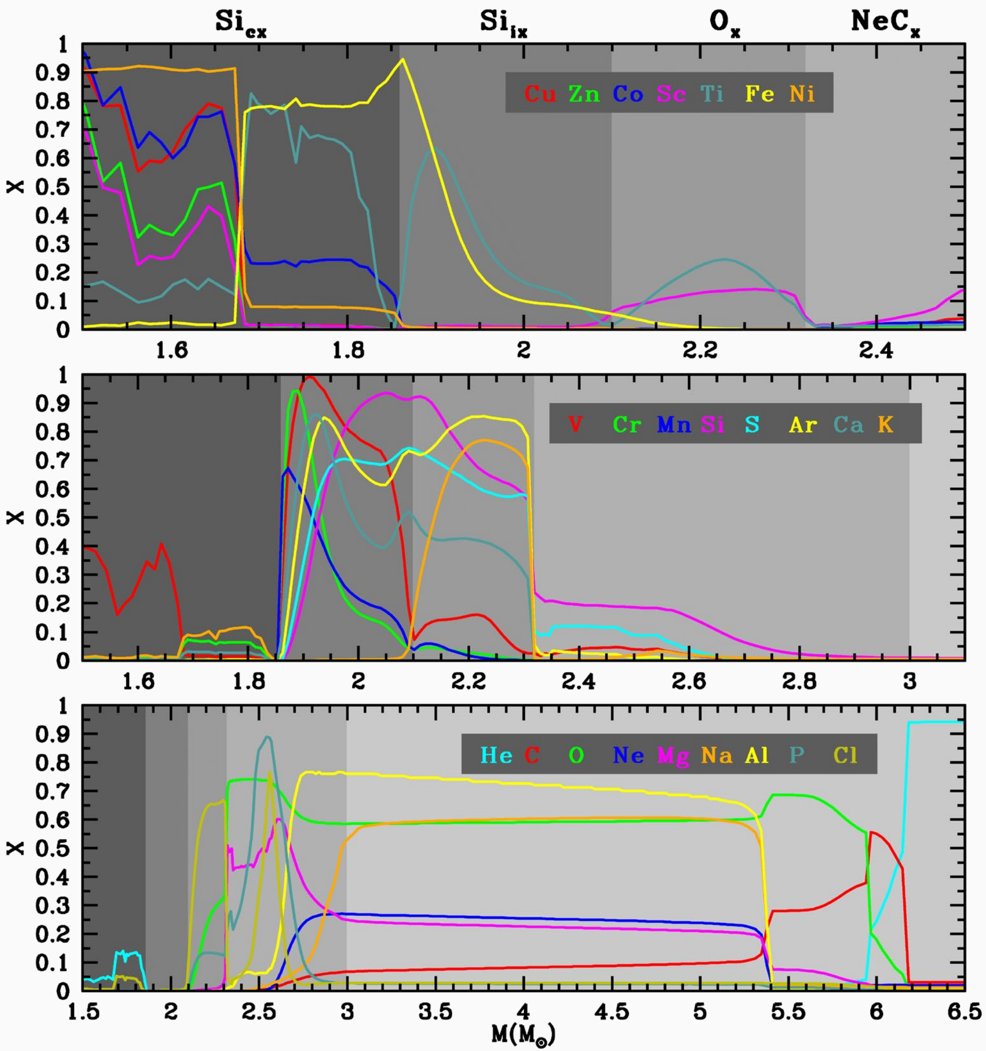


^{1}H ^{4}He ^{12}C ^{16}O ^{20}Ne ^{28}Si Cr Fe Ni
1.0
0.8
0.6
0.4
0.2
0.0
X
0
2
4
6
8
10
R(10^3km)

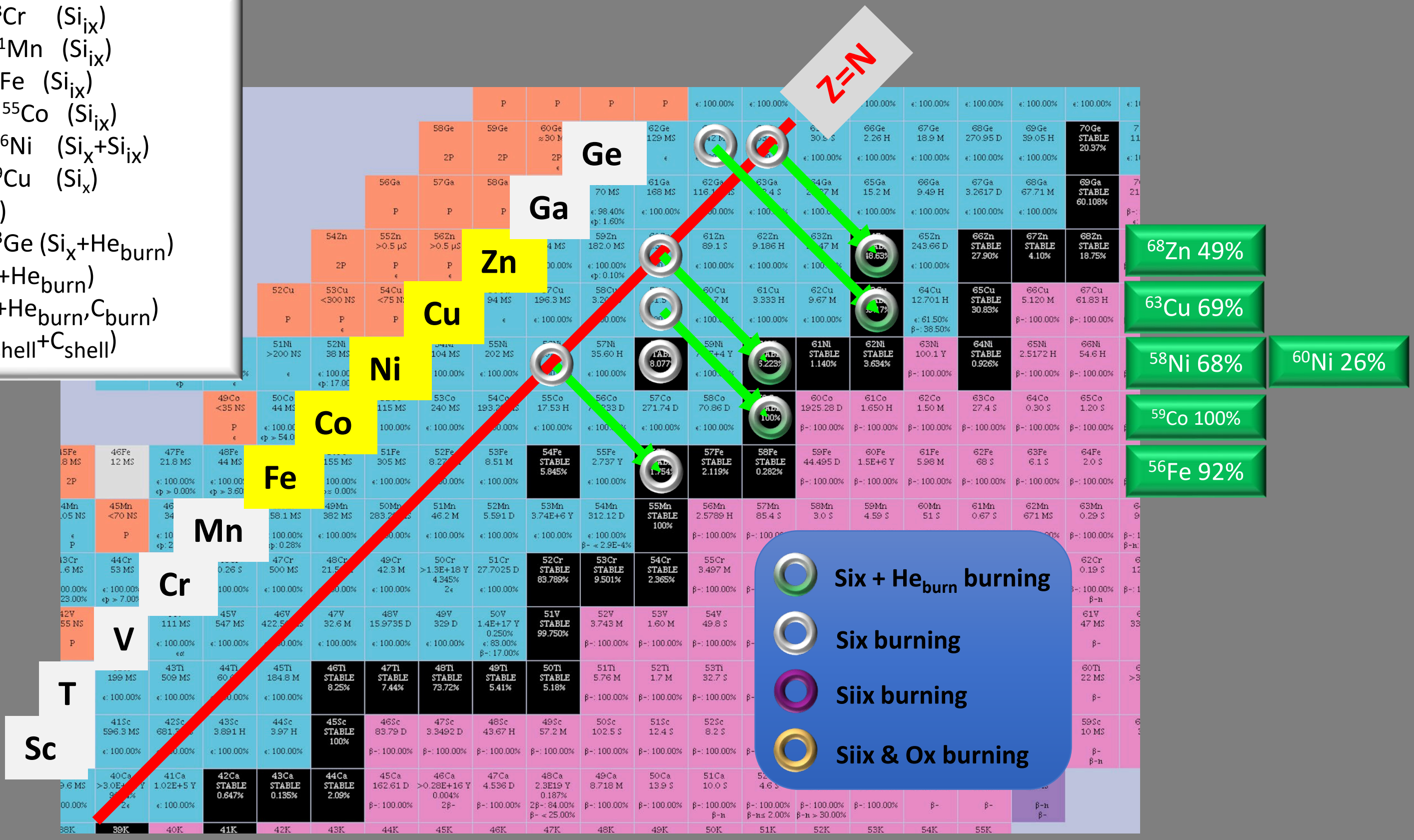


1H 4He 12C 16O 20Ne 28Si Cr Fe Ni
NSE Six
QSE Siix
2QSE Ox
Nex & Cx
5 BK
4 BK
3.2 BK
1.0
0.8
0.6
0.4
0.2
0.0
X
0
2
4
6
8
10
R(10^3 km)



Si_ex
Si_ix
O_x
NeC_x
Cu Zn Co Sc Ti Fe Ni
V Cr Mn Si S Ar Ca K
He C O Ne Mg Na Al P Cl
X
M(M☉)

Ti = ^{48}Ti = ^{48}Cr (Si_{ix})
V = ^{51}V = ^{51}Mn (Si_{ix})
Cr = ^{52}Cr = ^{52}Fe (Si_{ix})
Mn = ^{55}Mn = ^{55}Co (Si_{ix})
Fe = ^{56}Fe = ^{56}Ni (Si_x+Si_{ix})
Co = ^{59}Co = ^{59}Cu (Si_x)
Ni = ^{58}Ni (Si_x)
Cu = ^{63}Cu = ^{63}Ge (Si_x+He_{burn})
Zn = ^{64}Zn (Si_x+He_{burn})
+ ^{66}Zn (Si_x+He_{burn},C_{burn})
+ ^{68}Zn(He_{shell}+C_{shell})



Ti = ^{48}Ti = ^{48}Cr (Si_{ix})

V = ^{51}V = ^{51}Mn (Si_{ix})

Cr = ^{52}Cr = ^{52}Fe (Si_{ix})

Mn = ^{55}Mn = ^{55}Co (Si_{ix})

Fe = ^{56}Fe = ^{56}Ni (Si_x+Si_{ix})

Co = ^{59}Co = ^{59}Cu (Si_x)

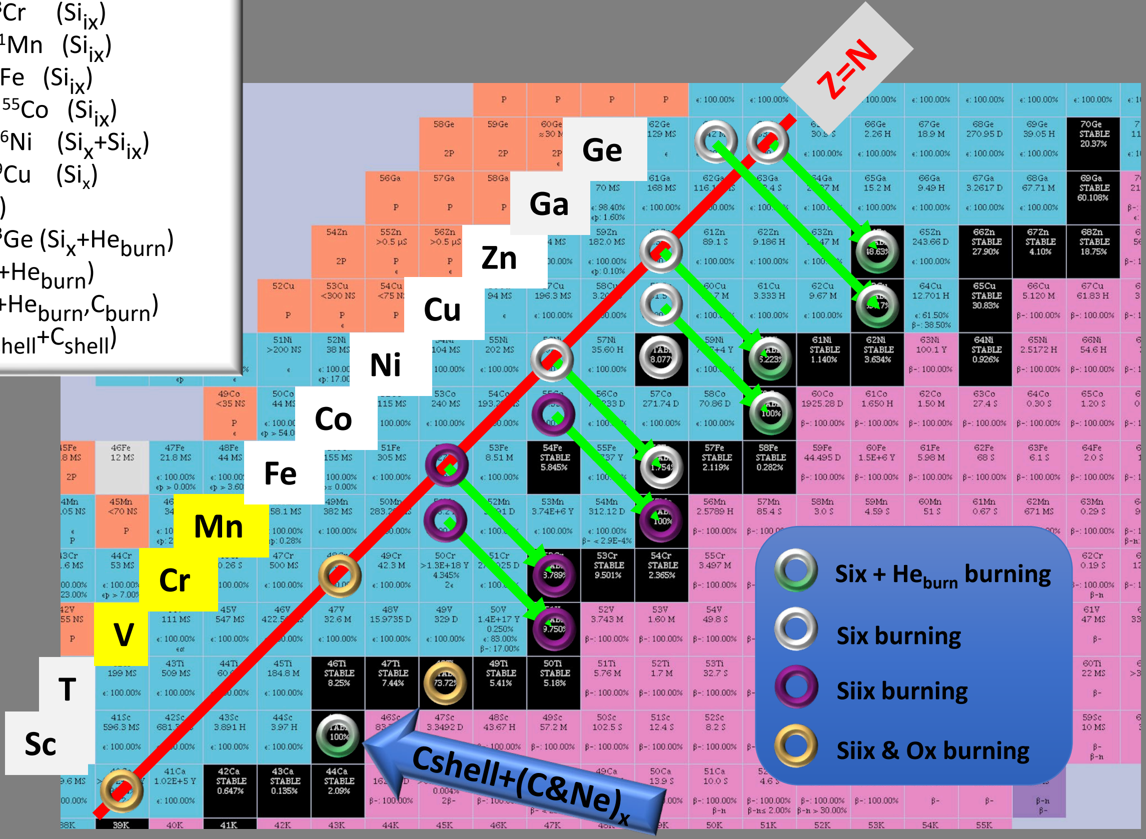
Ni = ^{58}Ni (Si_x)

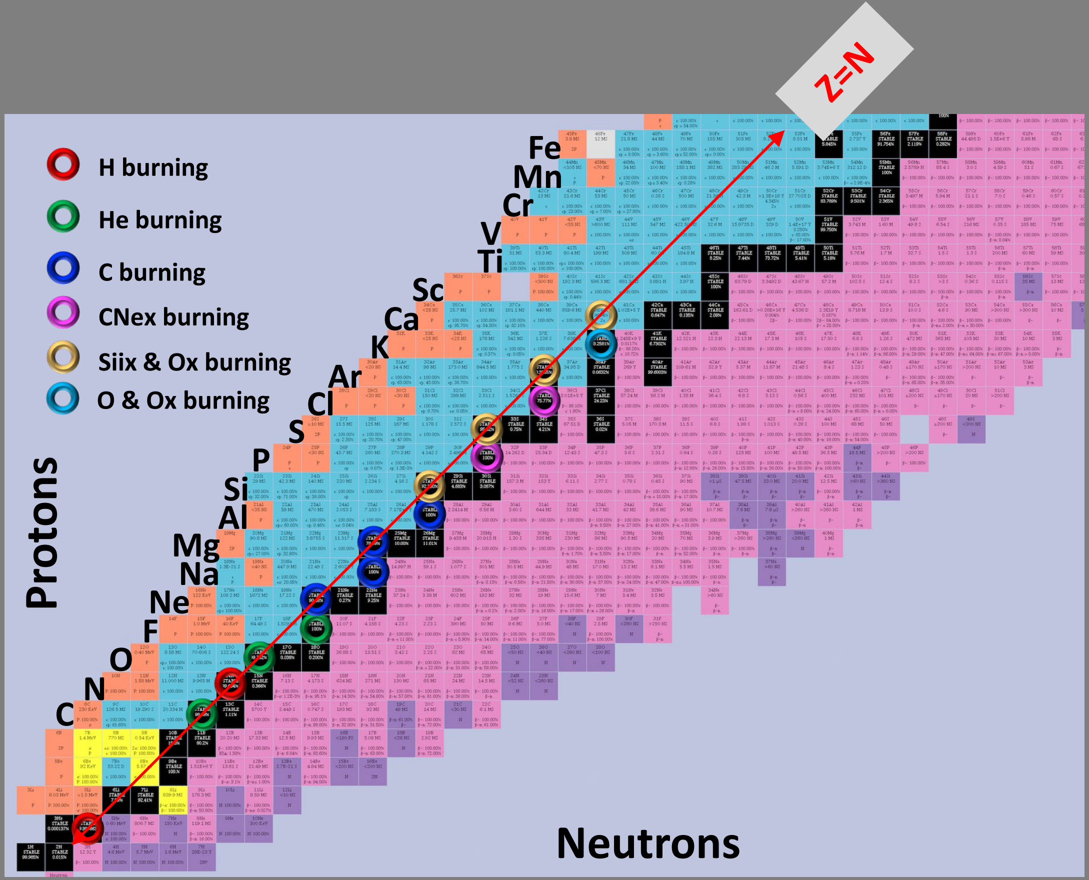
Cu = ^{63}Cu = ^{63}Ge (Si_x+He_{burn})

Zn = ^{64}Zn (Si_x+He_{burn})

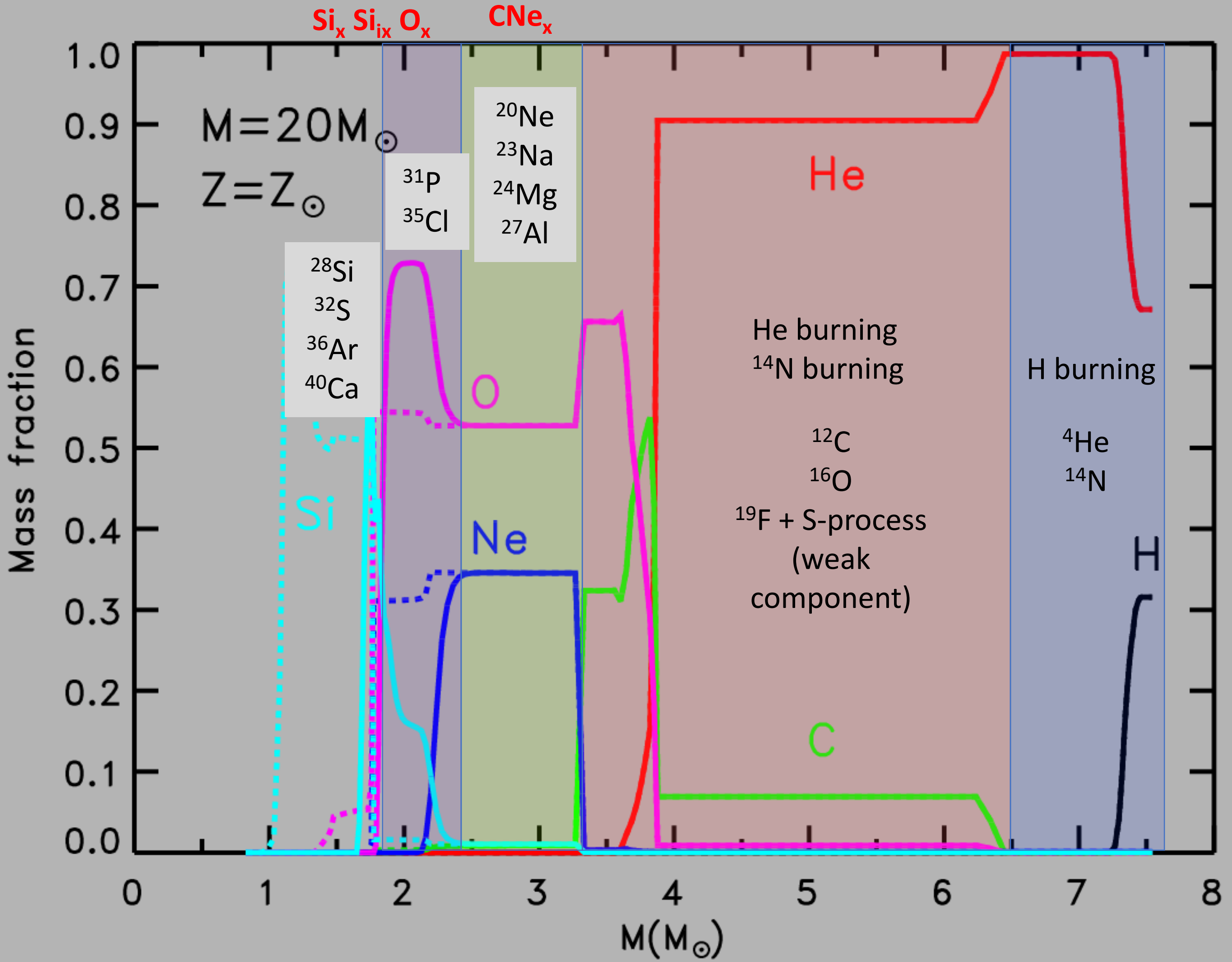
+ ^{66}Zn (Si_x+He_{burn},C_{burn})

+ ^{68}Zn(He_{shell}+C_{shell})





Z=N
H burning
He burning
C burning
CNex burning
Siix & Ox burning
O & Ox burning
Protons
Neutrons
Fe
Mn
Cr
V
Ti
Sc
Ca
K
Ar
Cl
S
P
Si
Al
Mg
Na
Ne
F
O
N
C


Si$_x$ Si$_{ix}$ O$_x$
CNe$_x$
M=20M$_\odot$
Z=Z$_\odot$
^{28}Si
^{32}S
^{36}Ar
^{40}Ca
^{31}P
^{35}Cl
^{20}Ne
^{23}Na
^{24}Mg
^{27}Al
He
He burning
^{14}N burning
^{12}C
^{16}O
^{19}F + S-process
(weak
component)
H burning
^{4}He
^{14}N
H
O
Ne
Si
C
Mass fraction
M(M$_\odot$)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0
1
2
3
4
5
6
7
8

recap

$T > 5 \cdot 10^9$ K

NSE: all nuclei are at the equilibrium
Complete Explosive Silicon burning

$Y_i = f(T, \rho, Y_e)$ $Y_e > 0.49$ $(\eta < 0.02)$

^{56}Ni The most abundant nucleous

Sc Ti Co Ni Zn Cu

$5 \cdot 10^9$ K $> T > 4 \cdot 10^9$ K

QSE: ^{28}Si is not ad the equilibrium
Incomplete Explosive Silicon burning

$Y_i = f(T, \rho, Y_e)$

V Cr Mn Si S Ar Ca

$4 \cdot 10^9$ K $> T > 3.3 \cdot 10^9$ K

2QSE: matter clustered in two groups, one peaked at ^{28}Si (99%) and the second one at Fe
Explosive Oxygen burning

$Y_i = f(T, \rho, Y_e)$

Si S Ar K Ca

$3.3 \cdot 10^9$ K $> T > 1.9 \cdot 10^9$ K

Explosive Neon and Carbon + C shell burning

Ne Na Mg Al P Cl

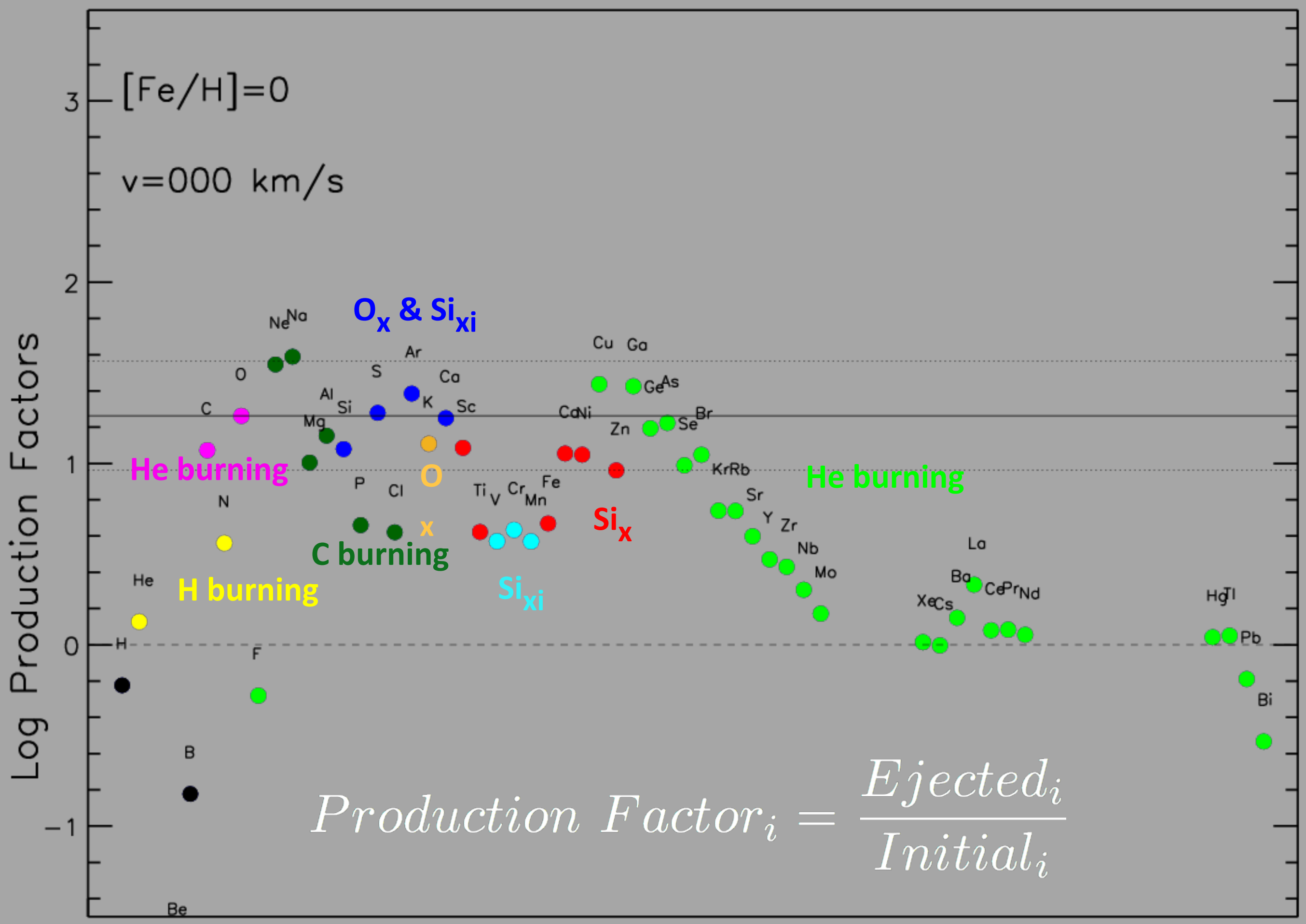
$T < 1.9 \cdot 10^9$ K

NO Explosive burning

Element	produced	destroyed
He (^{4}He)	$H_{c,s}$	$He_{c,s}$
C (^{12}C)	$He_{c,s}$	$C_{c,s}$
N (^{14}N)	$H_{c,s}$	$He_{c,s}$
O(^{16}O)	He_{c}	$C_{c,s}$
F (^{19}F)	He_{s}	
Ne (^{20}Ne)	C_{s}	Ne_{x}
Na (^{23}Na)	C_{s}	Ne_{x}
Mg (^{24}Mg)	C_{s}	Ne_{x}
Al (^{27}Al)	C_{s}	Ne_{x}
Si (^{28}Si)	Si_{ix} O_{x} Ne_{x}	
P (^{31}P)	Ne_{x} C_{s}	Ne_{x}
S (^{32}S)	Si_{ix} O_{x} Ne_{x}	
Cl	^{35}Cl O_{x} Ne_{x} - ^{37}Cl C_{s}	^{37}Cl Ne_{x}
Ar (^{36}Ar)	Si_{ix} O_{x}	
K (^{39}K)	He C_{s} O_{x}	O_{x}
Ca (^{40}Ca)	Si_{ix} O_{x}	

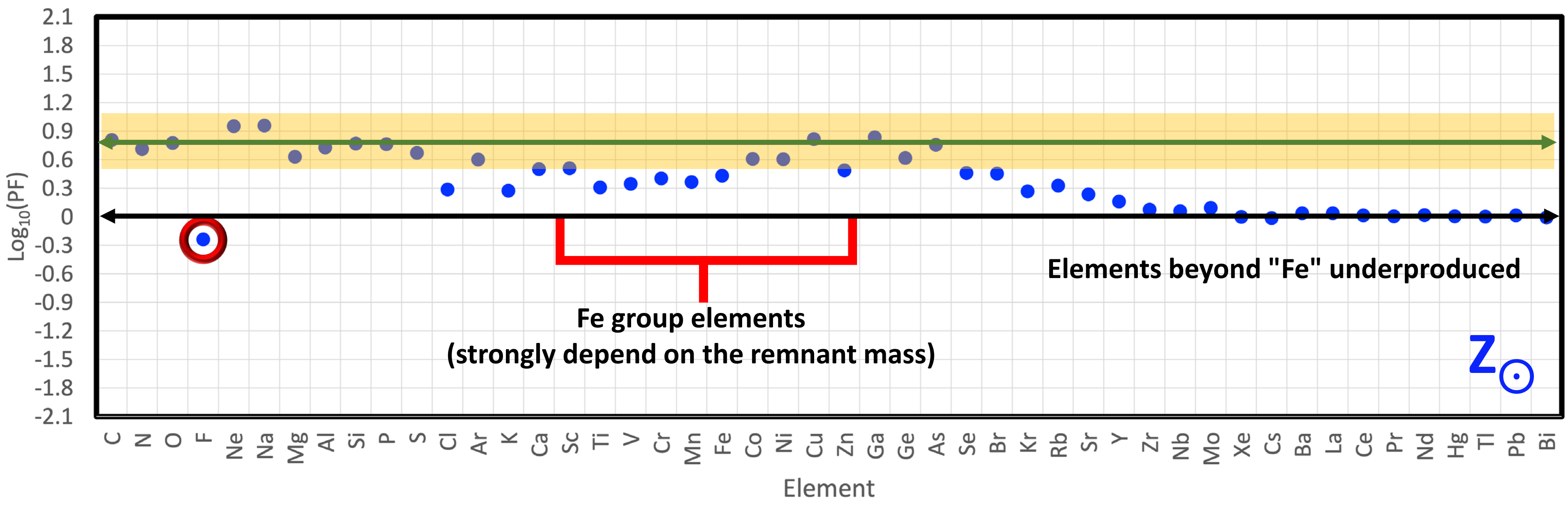
Element	produced	destroyed
V (^{51}V)	Si_{ix}	
Cr (^{52}Fe)	Si_{ix}	
Mn (^{55}Fe ^{55}Co)	Si_{ix}	
Sc (^{45}Sc, ^{45}Ca)	He C_{s} Si_{x}	Ne_{x}
Ti (^{48}Cr)	O_{x} Si_{x} Si_{ix}	
Fe (^{56}Ni ^{56}Fe ^{54}Fe)	Si_{ix} O_{x}	
Co (^{59}Ni)	He_{c} Ne_{x} Si_{x}	
Ni (^{58}Ni)	Si_{x}	
Cu(^{63}Cu)	He_{c} Ne_{x} Si_{x}	
Zn(^{64}Zn)	He_{c} Ne_{x} Si_{x}	

Solar metallicity


[Fe/H]=0
v=000 km/s
Log Production Factors
3
2
1
0
−1
H
He
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Y
Zr
Nb
Mo
Xe
Cs
Ba
La
Ce
Pr
Nd
Hg
Tl
Pb
Bi
O_x & Si_xi
He burning
H burning
C burning
O x
Si_xi
Si_x
He burning
$Production\ Factor_i = \frac{Ejected_i}{Initial_i}$

Production Factors produced by a generation of massive stars:

$$PF = \frac{X^i_{ejecta}}{X^i_{initial}} = \frac{Y^i/M_{ejected}}{X^i_{initial}}$$



Critical masses (model dependent)